FACULTY OF AGRONOMY AND FORESTRY ENGINEERING

Study of the Land Use, Land Cover and Climate Effects on Water Availability in the Incalaue River Basin in Niassa Special Reserve, Northern Mozambique

By

Ezrah Natumanya

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Forestry Resources

Maputo

December 2023

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DECLARATION

I, Ezrah Natumanya, hereby declare that this thesis has never been presented for obtaining any degree or otherwise and that it is a result of my individual work. This is submitted in partial fulfilment of the requirements for the degree of PhD in Forest Resources in the Department of Postgraduate Studies under the Faculty of Agronomy and Forestry Engineering of Eduardo Mondlane University.

Ezrah Natumanya

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Maputo, December 07, 2023

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DEDICATION

I dedicate this PhD thesis to my mother, Mrs. Kobukama Edry Rukare who has always lovingly believed in me; and endlessly kept me in her prayers to succeed in academics especially during this PhD journey despite challenges along the way.

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II. Mapping Landscape Positions and Relevance of Two Dambo-Springs in Incalaue River Basin in Niassa Special Reserve, Mozambique: Information for Drought Water Shortage Effects Management. *Journal of Environmental Science and Engineering*, B 10 (2021) 211-226. doi:10.17265/2162-5263/2021.06.001

III. Using the SWAT model and field data to determine the potential of NASA-POWER data for modelling rainfall runoff in the Incalaue river basin. *Journal of Computational Water, Energy, and Environmental Engineering* (2022), ISSN Online 2168-1570. ISSN print: 2168-1562. https://doi.org/10.4236/cweee.2022.112004

IV. Assessment of conservation status of riparian vascular plant species in a dry season exposed flood plain area of Incalaue river catchment, Niassa Special Reserve, Northern Mozambique. *Environ. Res.: Ecol.* **3** 015001 https://doi.org/10.1088/2752-664X/ad0e7a

V. Understanding land use, land cover and climate effects on rainfall runoff source areas in Incalaue catchment, Niassa Special Reserve, Northern Mozambique (Accepted manuscript). *MDPI Sustainability Journal*. Sustainabilitty-993116-revision 2nd (*https://www.mdpi.com/journal/sustainability*).

SUMARIO

O uso e Cobertura da Terra (LULC, do acrónimo em inglês) são os principais determinantes dos processos hidrológicos em qualquer zona climática e variam devido a actividades naturais ou antropogénicas e podem causar alterações na disponibilidade de água numa paisagem. Este estudo avaliou os efeitos do LULC e do clima na disponibilidade de água na bacia hidrográfica do rio Incalaue (697,02 km^2) na Reserva Especial do Niassa (REN). Este estudo foi importante para orientar os gestores da NSR sobre as necessidades de conservação da água e gestão de LULC, especialmente com a expansão dos assentamentos populacionais humanos e do uso da terra. Os resultados foram publicados em três artigos e duas manuscrito foi aceite para publicação. Este estudo foi importante para orientar os gestores da NSR sobre as necessidades de conservação da água e gestão de LULC, especialmente com a expansão dos assentamentos populacionais humanos e do uso da terra. A caracterização à escala da paisagem do LULC e das influências do declive do solo foi utilizada para avaliar o escoamento das chuvas reflectido no caudal do rio. Dois artigos abordaram a classificação do LULC e avaliaram a conectividade da paisagem e a sua relação com as fontes e disponibilidade de água. O terceiro artigo avaliou o escoamento das chuvas e utilizou dados de satélite de detecção remota para derivar tendências, uma vez que a bacia hidrográfica nunca foi medida. Um manuscrito sobre os efeitos do LULC e do clima nas áreas de origem das chuvas e escoamento foi aceite para publicação. Neste estudo, o Uso da Terra e Mudança de Cobertura (LULCC), do acrónimo em inglês) foi caracterizado por meio de imagens do satélite Landsat ETM/TM. A análise do LULC foi feita utilizando imagens de detecção remota, Sistemas de Informação Geográfica (GIS) e observações de campo. A Ferramenta de Avaliação de Solo e Água (modelo SWAT, do acrónimo em inglês) foi utilizada para simulações hidrológicas; e os softwares Microsoft Excel e Statistical Package for the Social Sciences (SPSS) foram utilizados nas análises estatísticas. Ao manter fixos os valores óptimos do modelo enquanto se varia o LULC na Ferramenta de modelo SWAT, as alterações no escoamento da precipitação modelado foram tomadas para reflectir os impactos do clima. O estudo encontrou mudanças no LULCC usando imagens amostradas de 2001, 2009 e 2019, com destaque para a área coberta por vegetação mais alta na ordem de Floresta de Baixa Densidade (+15,94%) > Floresta de Alta Densidade (-4,15%) > Florestas de Montanha (-5,37)> Florestas de Média Densidade (-6,46%). Foram coletados dados de trabalho de campo (2019 – 2021). Houve uma relação estatisticamente significativa entre precipitação e escoamento superficial (P = 9,21E-37), bem como uma variação sazonal significativa na produção de água subterrânea nas nascentes (P = 1,29E-10) usando dados de campo. Não houve grandes alterações no escoamento das chuvas no período de 2001 a 2021; apenas com pequenas variações apenas nos meses de março (-0,17%), novembro (+0,73%), dezembro (+0,05%) e janeiro (+0,1%). A bacia hidrográfica tem 20 Unidades de Resposta Hidrológica (HRUs) dominantes e 241 individuais em 11 sub-bacias hidrográficas. A análise da contribuição parcial mostrou a influência do LULC e do clima na precipitação-escoamento para 0,35 e 0,21, respectivamente. Descobriu-se que as nascentes de água subterrânea são fontes de água indispensáveis tanto para a vida selvagem como para as pessoas na estação seca (Junho a Novembro). As contribuições únicas para a ciência incluíram este ser o primeiro estudo de avaliação da disponibilidade de água, somando-se aos muitos estudos LULC existentes, explorando ao mesmo tempo o potencial para a monitorização remota da precipitação e da relação do fluxo do rio, bem como a proporção da contribuição parcial do LULCC e do clima para a água do rio. Este estudo avaliou eficazmente a disponibilidade de água subterrânea e as relações LULC anteriormente desconhecidas; e fez recomendações para a sua conservação como manchas de paisagem com valor de conservação para as pessoas e a vida selvagem.

Palavras-chave: Clima, Paisagem, Nexo, Hidrologia, Disponibilidade de Água

ABSTRACT

Land use and land cover (LULC) is a major determinant of hydrological processes in any climate zone and varies due to natural and anthropogenic activities which can cause changes in water availability in a landscape. This study assessed the effects of LULC and climate on water availability in the Incalaue river catchment (697.02 sq.km) in Niassa Special Reserve (NSR). This study was important to guide NSR managers on water conservation needs and LULC management especially with expanding human population settlements and land use. Landscape-scale characterization of LULC and soil-slope influences were used to assess rainfall runoff as reflected in river flow. Results were published in three papers and two manuscript are at late stages of publication process. Two papers addressed LULC classification and assessed landscape connectivity and its relationship with water sources and availability. The third paper assessed rainfall runoff and used remote sensing satellite data to derive trends since the catchment is ungauged. A research manuscript on Understanding LULC, and climate effects on rainfall-runoff source areas has been accepted for publication. In this study, LULCC was characterised using Landsat EMT/TM satellite images. Analysis of LULC was done using remote sensing imageries, Geographical Information Systems (GIS) and field observations. Soil and Water Assessment Tool (SWAT model) was used for hydrologic simulations; and Microsoft Excel and Statistical Package for the Social Sciences (SPSS) software were used in statistical analyses. By keeping the optimal values of the model fixed while varying LULC in Soil and Water Assessment Tool (SWAT model), changes in modelled rainfall runoff were taken to reflect the impacts of climate. The study found land use and land cover changes (LULCC) using sampled images of 2001, 2009 and 2019 with highlights being area covered by taller vegetation in the order of Low Density Woodland (+15.94%) > High Density Woodland (-4.15%) > Mountain Forests (-5.37)> Medium Density Woodland (-6.46%). Fieldwork data was collected (2019 – 2021). There was a statistically significant rainfall and runoff relationship (P = 9.21E-37) as well as significant seasonal variation in groundwater spring yields (P=1.29E-10) using field data. There was no major change in rainfall runoff for the period 2001 to 2021; only with minor changes only in the months of March (-0.17%), November (+0.73%), December (+0.05%) and January (+0.1%). The catchment has 20 dominant and 241 individual Hydrologic Response Units (HRUs) in 11 sub-catchments. Partial contribution analysis showed the influence of LULC and climate on rainfall-runoff to 0.35 and 0.21

respectively. Groundwater springs were found to be indispensable water sources for both wildlife and people in the dry season (June to November). The unique contributions to science included this being the first water availability assessment study adding to the many existing LULC studies while exploring potential for remote monitoring of rainfall and river flow relationship as well as the ratio of partial contribution of LULCC and climate to river water. This study effectively assessed groundwater water availability and LULC relations previously unknown; and made recommendations for their conservation as landscape patches of conservation value for people and wildlife.

Keywords: Climate, Landscape, Nexus, Hydrology, Water Availability

LIST OF ABBREVIATIONS

ABBREVIATION	FULL
ASTER	Advanced Space-borne Thermal Emission and Reflection Radiometer
ARD	Analysis Ready Data
CBD	Convention on Biological Diversity
CERES	Clouds and the Earth's Radiant Energy System
DEM	Digital Elevation Model
DSMW	Soil Map of the World
DUAT	Direito de Uso e Aproveitamento da Terra
ES	Ecosystem Service
ET	Evapotranspiration
FAO	Food and Agriculture Organization of the United Nations
GMAO	Global Modelling and Assimilation Office
HRU	Hydrologic Response Unit
IIAM	Investigação Agrária de Moçambique
INIA	National Institute of Agronomic Research in Mozambique
IFAD	International Fund for Agricultural Development
IWRM	Integrated Water Resources Management
GIS	Geographical Information System
LAI	Leaf Area Index
LP-DAAC	Land Processes Distributed Active Archive Centre
LULC	Land Use and Land Cover
LULCC	Land Use and Land Cover Change
MEaSUREs	Making Earth System Data Records for Use in Research Environments
MICOA	Ministry for Coordination of Environmental Affairs of Mozambique
NASA	National Aeronautics and Space Administration

NCP	Niassa Carnivore Project
NSE	Nash–Sutcliff Efficiency
NSR	Niassa Special Reserve
NDVI	Normalized Difference Vegetation Index
POWER	Prediction of Worldwide Energy Resources
RSB	Surface Radiation Budget
STRM	Shuttle Radar Topographic Mission
SWAT	Soil and Water Assessment Tool
USGS	United States
UTM	National Institute of Agronomic Research
WCS	Wildlife Conservation Society

EXPLANATIONS OF KEY TERMS

Ecosystem: A biological functional unit where the living organisms interact with each other and the surrounding environment.

Heterogeneity: Variation both within and between land use/cover types and classes in a landscape.

Landscape: Geographical representation of geology and land landforms in the physical elements such as mountains, hills, water bodies, natural vegetation and human land use.

Land use: Any activities carried out by humans with the intention to obtain products and/or benefits through using land resources.

Land cover: Elements on the earth's surface such as vegetation (natural or planted); man-made constructions (buildings, etc.), water, bare rock (inselbergs) and roads.

Runoff: Part of the water cycle that flows over land as surface water instead of being absorbed into groundwater or evaporating. The term was used in this study to refer to rainfall water that flows over land and reaches the river intermittently referred to as runoff and rainfall runoff as the section and sentence write-up demanded.

River catchment and river basin: These were used interchangeably in literature review to keep originality. River catchment in particular is used in this study to refer to the portion of landscape drained by a river and its tributaries and flows downhill into one another and eventually into river.

Nexus: A connection or series of connections linking two or more things which in this study were land use, land cover, water and climate.

Water availability: This was used as a broad term encompassing easily accessible biophysical supply of water to meet demands.

CHAPTER ONE
INTRODUCTION

1.1 Background and site description

The study was conducted in catchment area of river Incalaue which is one of the tributaries of river Lugenda in Northern Mozambique (Figure 1). River Lugenda is a major surface water body in the Niaassa Special Reserve (NSR). River Lugenda is also a tributary of river Rovuma. River Lugenda flows from Lake Chiuta and is the largest tributary of the Ruvuma River that flows along the border between Mozambique and Tanzania.

Incalaue catchment (697.02 km^2) lies between the latitudes 12° 8' 40" N and 12° 22' 40" N; and 37° 21' 00" E and 37° 39' 40" E partly in the administrative posts of Mecula-Sede and Matondovela. The catchment is mainly a woodland area with human settlement areas of Lisongole and Ntimbo 1 as well as the NSR main administrative campsite of Mbatamila in the river catchment.

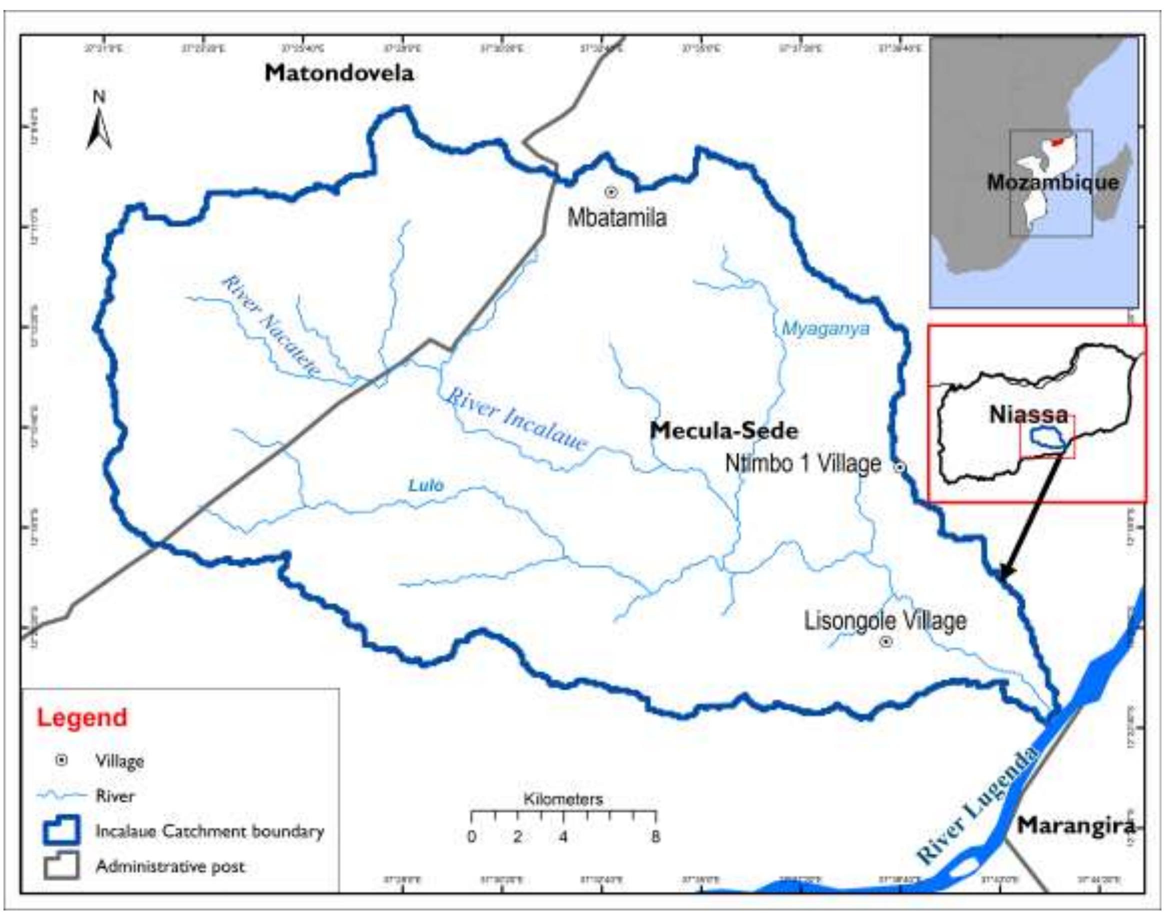

Figure 1: Location of Incalaue river catchment

Incalaue is part of a wider network of rivers draining the NSR landscape (Figure 2). The NSR (42,300 km^2) is partly in Cabo Delgado and Niassa Provinces (Mittermeier et al., 2003).

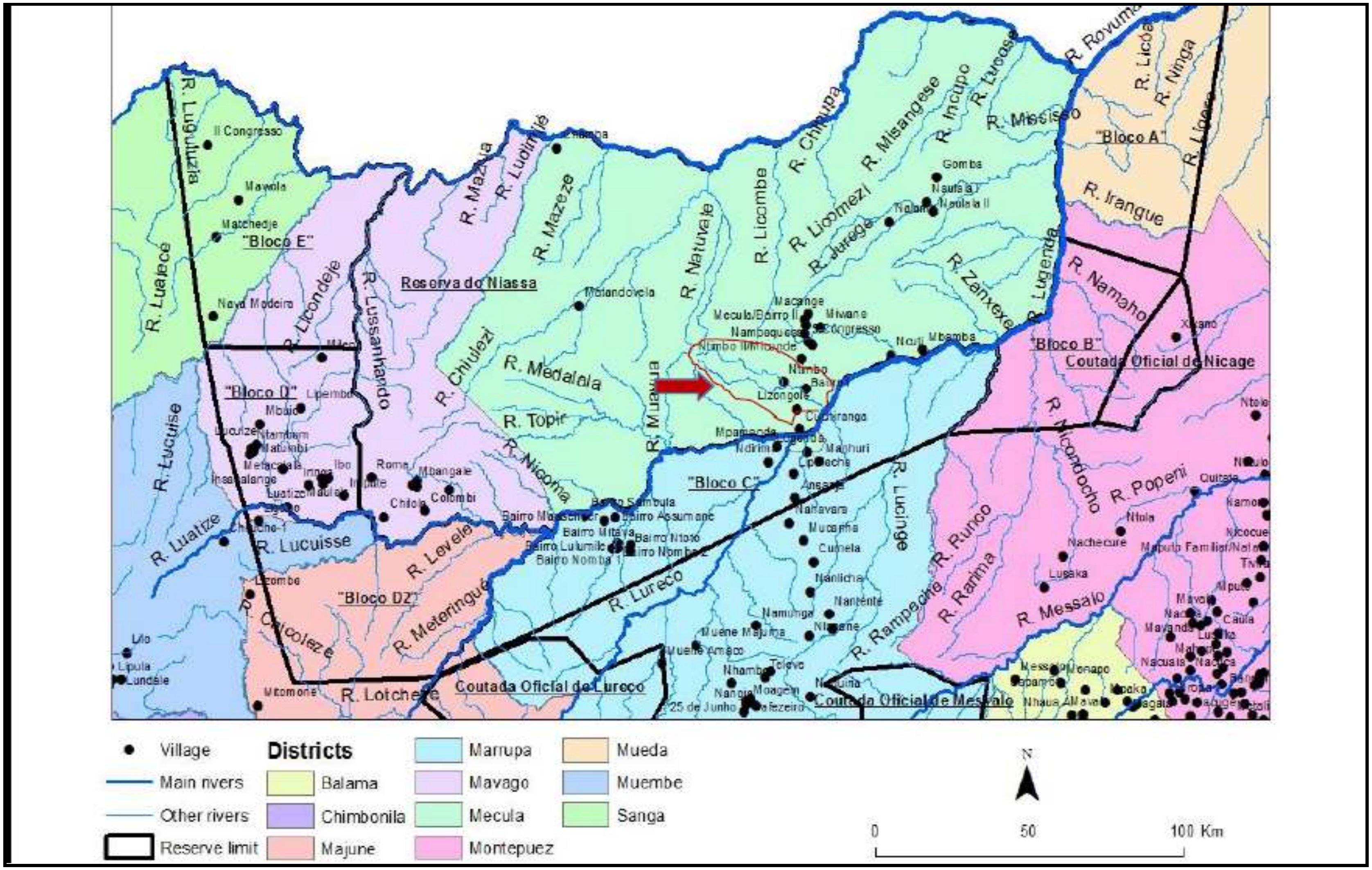

Figure 2: The network of rivers in Niassa Special Reserve
(Arrow points at Incalaue location of catchment)

1.1.1 Vegetation

The vegetation in NSR is largely dominated by Miombo ecosystem, which is more or less dense deciduous woodlands with limited shrub layer (Ribeiro et al., 2013). Vegetation sheds leaves during the dry seasons for most species and localities. Its densities vary, with woodlands, open woodlands and wooded grasslands generally characterized by the presence of woody vegetation. Vegetation is dominated by a small group of species such as *Brachystegia spp., Julbernardia globiflora or Diplorrynchus condylocarpon* (Mbanze et al., 2019a). The NSR has the largest and best preserved tracts of miombo woodland left in Africa (Allan et al., 2017). The most ecologically important tree species in NSR by the Importance Value Index (IVI) are *Julbernardia globiflora* (Benth.) Troupin, *Diplorhynchus condylocarpon* (Mull. Arg) and *Brachystegia boehmii Taub* (Ribeiro et al., 2013).

A comprehensive vegetation cover classification in the NSR was adopted from existing literature for use in this study (Ribeiro et al., 2008). According to the study just mentioned, the vegetation classes in the area are Medium Density Woodland (MDW), High Density Woodland (HDW), Wooded Grasslands (WGL), Low Density Doodland (LDW), Mountain Forests (MFS) and Wetland (WET). This classification of vegetation structure and canopy spacing was given by that study as shown as below:

i. High density woodlands: The crown cover of the upper stratum is greater than 75% and the herbaceous layer is poorly developed or totally absent.
ii. Medium density woodlands: The crown cover of the dominant layer ranges from 50 to 75%. A moderate dense shrub layer is normally present with a ground stratum normally sparse.
iii. Low density woodlands: The upper layer crown cover is between 25 and 50% and a well–established herbaceous stratum is normally present.
iv. Wooded grasslands: Mosaic of grass and other herbs with scattered or grouped woody plants and trees (crown coverage from 10 to 20%).
v. Mountain forests: More than 80% tree cover.

1.1.2 Soil

A national soil texture characterisation by Food and Agriculture Organization of the United Nations (FAO); and an existing soil texture map from the Government of Mozambique were adopted for soil characterisation in the area (Figure 3a). An official government record was accessed as a hardcopy map from (Instituto de Investigação Agrária de Moçambique (IIAM) and digitized for the area (Figure 3b). The IIAM soil texture map above was developed in a research project on the status of soil resources in resources in Mozambique landscapes (Mafalacusser, 2013). The study area coverage of soil texture classes was determined after digitization from the available Niassa provincial soil texture map (Table 1).

Table 1: Soil textual in Incalaue catchment

Soil textural class	Area (Sq. Km)
Soils with peaty layer (A)	167.24
Shallow soils on acidic rocks (I)	11.28
Brown soil with coarse texture (KA)	190.23
Brown soil of medium texture (KM)	221.20
Total	697.02

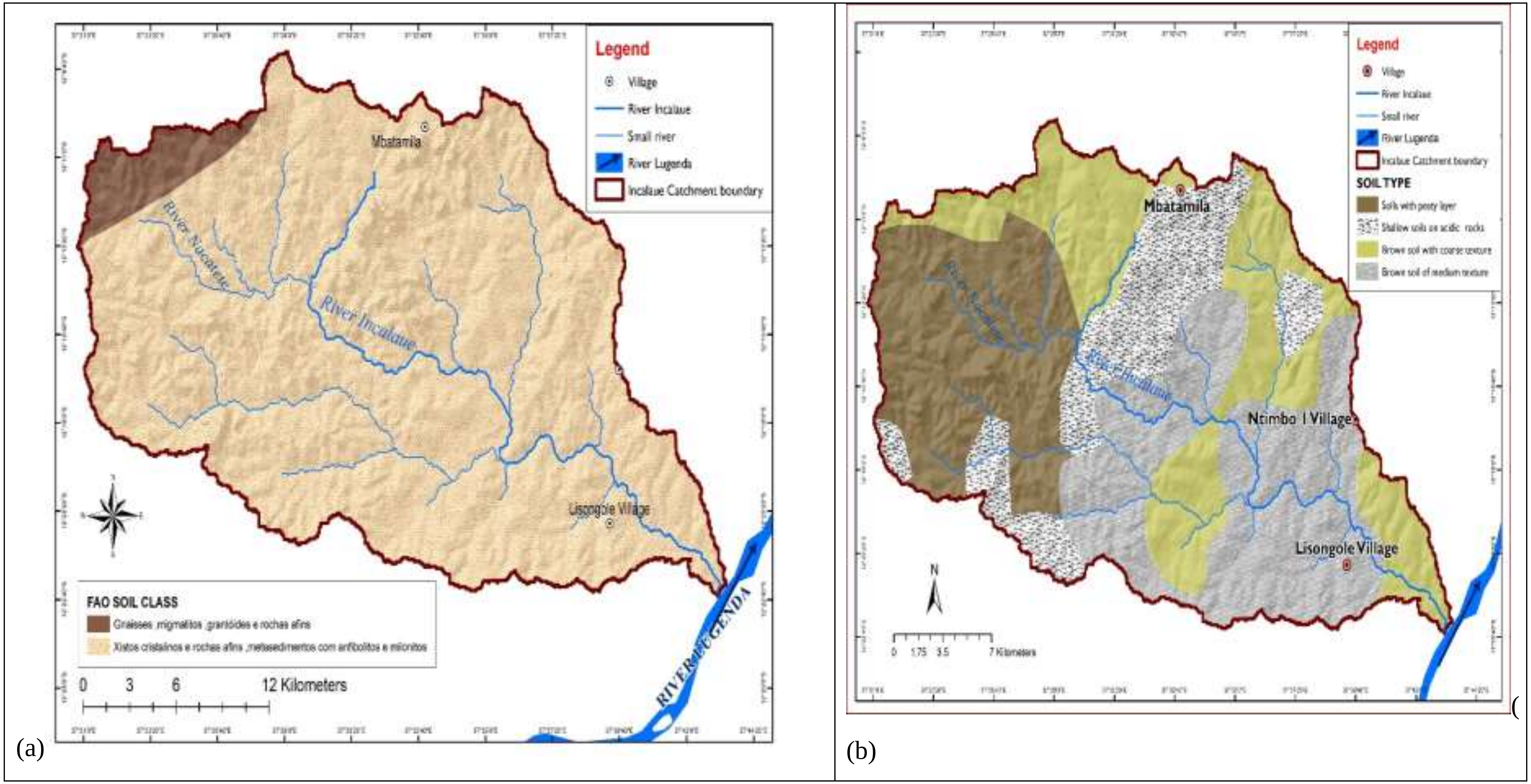

Figure 3: FAO soil type (a); and texture from IIAM (b) maps

1.1.3 Climate and water resources

The area has a tropical sub-humid climate with unimodal rainfall seasonality (Ribeiro et al., 2008b). In this climate, temperature follows the same trend as rainfall (Figure 4). A large part of annual rainfall occurs mostly for 4–5 months between December to April (Mbanze et al., 2015).

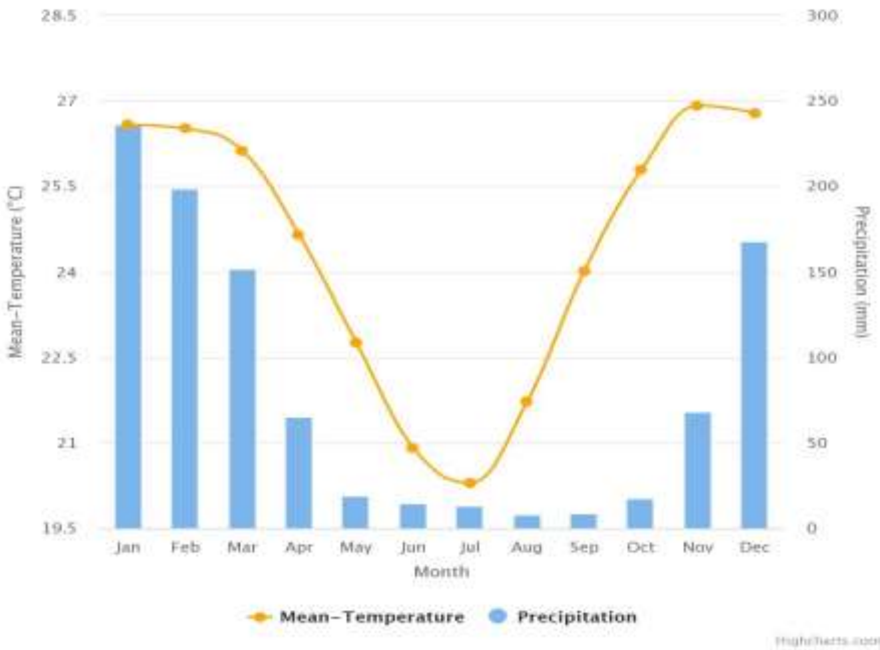

Figure 4: Mean monthly rainfall and temperature of Northern Mozambique

(Data from World Bank Climate Knowledge Portal)

There is no systematic water supply network and majority of communities in NSR outside major towns depend on rivers like Incalaue for livelihoods. The local communities depend on water from the river both for household use and irrigation of crops; and biodiversity for their livelihood and subsistence needs (Allan et al., 2017).

Incalaue river is located in a wildlife migration zone to a bigger and permanent Lugenda river downstream during the dry season as the small rivers get dry in an area with a tropical sub-humid and drought-prone climate (Allan et al., 2017). The area has both strong rainy and harsh dry seasons. In the dry season, the river and ceases flow some times and water remains in a few water pools (Figure 5). The drying of the river, with water remaining in small pools poses and human-wildlife interaction situation by making people to only depend on a few water points that remain including streams from some groundwater springs in areas near dambos draining into the river (von der Heyden & New, 2003).

Figure 5: Pictorial view of the seasonal landscape characteristics

When the river water reduces and finally flow stops in this seasonal river, groundwater springs in dambo areas become the source of water for communities. These dambo are areas remain with wet vegetation unlike other areas in the dry season. Dambos occur mainly in the wooded grasslands and grassland vegetation areas and provide a wide range of other Ecosystem Services (ES), including water for animal species (Mbanze et al., 2019b). These dambo areas contribute to biomass production and protection by supporting water availability for dependent ecosystems (Brauman et al., 2007; Brockerhoff et al., 2017; Hofmeister et al., 2019).

1.2 Problem statement

Climate and change effect on water availability in NSR and regional miombo ecosystem remain unknown with a need to document specific evidence (Franklin et al., 2016). Climate and LULCC affect landscape hydrology processes and have an impact on water provision ecosystem services (ES) (Elmhagen et al, 2015; Cowles et al. 2018). There are not many studies that have conducted on landscape influences on water availability in NSR which is one of the important conservation areas in Mozambique. This knowledge is even more important given the nexus of people-wildlife-water in the area. The area has human population settlements and towns which means population growth and LULCC over time and related need for water availability for people and wildlife. The miombo woodland landscapes are diverse with several rivers and other sources of water including dambos contributing to the water-availability for people and wildlife.

Incalaue river catchment has human settlement and like many parts of NSR was already characterised by dry season water shortages and uncertainty especially in the dry season (Fauna et al., 2012; Allan et al., 2017). There is uncertainty regarding factors influencing river flow seasonal dynamics and general surface water availability. The catchment area has very strong dry season (May to November) where the river runs dry and water remains in a few pools. The sharing, competition, risks and challenges of access to the river water pools for communities in the dry season makes people and some wildlife too dependent on ground water springs in dambo areas. Despite this nexus between people-wildlife-water, there is still a scientific knowledge gap on inter-season water availability drivers and dynamics beyond visible effects and this is important information for land use management needs to support conservation of these water source hotspot areas for people and wildlife. There is a knowledge gap on rainfall runoff relationship and river flow trends and this all this is necessary to support decision making in land use planning that considers landscape hydrology. Land use planning that considers landscape hydrology requires data on long term hydrologic behaviour to be able to make reliable and sustainable decisions. The catchment is ungauged and located in a hard-to-reach wildlife risky area and there is no nearby gauged catchment which means that effective hydrologic modelling studies are needed for studies on and river behaviour influences. There is need to understand river flow behaviours and factors affecting ecosystem water retention in this hotspot area for land use planning given the areas has human settlements and land use. No satellite data applicability studies have been done for potentially use of effective internationally recognised satellite datasets.

There are a lot of studies on influences on LULCC on river flow in NSR but there have not been many on community water availability and access. This was identified by this research study as a growing challenge for conservation efforts with increasing community development as well as land use and climate change pressures. There are streams from groundwater springs near dambo areas which are vegetation zones that take longer in dry seasons making them important for wildlife and people but the hydrology of these areas is not well known. The contribution of landscape drainage to dambo springs and eventually water availability with reference to LULC has not been well explored in Incalaue and generally part of the miombo region in Mozambique.

1.3 Objectives and research questions

1.3.1 Objectives

The goal of this research was to *investigate land use and land cover factors that influence rainfall runoff and surface water availability in Incalaue river catchment.*

The specific objectives of the research were to:

i. Assess Land Use and Land Cover (LULC) in rainfall runoff contribing areas in the Incalaue catchment.
ii. Establish rainfall runoff relationship and influences on water source areas in the Incalaue catchment.
iii. Determine the partial contributions of rainfall and LULC to river flow in the Incalaue catchment.

1.3.2 Research questions

The research questions were:

i. What are the LULC strata in the river flow source areas in Incalaue catchment?
ii. What are the LULC indicators of environment wetness and connectivity in the catchment?
iii. What are the landscape positions and relevance of groundwater sources?
iv. What is the rainfall and runoff relationship in the catchment?
v. What are the soil and slope properties of influence on rainfall runoff in the catchment?
vi. What are the relative influences of rainfall and LULCC to river flow?

1.4 Justification and significance

There is a need to document specific evidence of ecosystem conservation and change effect on water resources in the miombo ecosystem in Niassa region and this has been well recommended by previous research (CBD, 2010; Franklin et al. 2016). Understanding of processes that contribute to ecosystem water availability is needed to inform sustainable conservation of water source areas in NSR.

The Incalaue river catchment hosts human population who benefit from surface and groundwater ES so land use management must be informed by landscape hydrology understanding otherwise it becomes a threat to both people and wildlife (Raihan & Haroon, 2016; Brauman et al., 2017). Seasonal sub-catchments of river Lugenda like Incalaue are always important conservation hotspots as wildlife migration zones in the dry season to permanent water sources. Landscape hydrogeology influences natural stream and river flows and these are important in nature reserves for water provision ES. Human populations in villages within the study area depend on rain-fed subsistence agriculture and rivers as well as groundwater springs and river water for household uses and agriculture. Incalaue catchment covers only 1.65% of NSR but it is a conservation hotspot because of its relevance as a wildlife dry season migratory zone and land use since there are human settlement areas. The river is the main source of water for wildlife and people staying in the area especially in the mid and end of dry season. This study explored the dynamics of soil, water and vegetation in patches and expression of water availability in the landscape as well as influencing factors of water provision ES in the catchment. To achieve this, it is important to understand the scales and influences of hydrologic process of rainfall runoff draining into the river and catchment area water storage characteristics. This involves quantifying the variability, change patterns and effects of land use and relief as well as climate effects on water availability.

Incalaue river catchment hosts human populations with LULC including agriculture and infrastructure like roads in and around settlement areas all of which are a threat to natural ecosystems. Presence of human settlement area and related socio-economic development is also a major risk of environmental degradation. Environmental degradation in wildlife conservation areas leads to shifts in relative abundance of animal species, which are key for seed dispersal and thus vegetation species recruitment (Pei et al., 2018). Understanding the relationship between vegetation and soil is an important indicator in the ecosystem management and restoration in land use/cover management (Zhang et al., 2015; Tang et al., 2016).

Climate and LULC affect landscape hydrology processes and have an impact on biodiversity and Ecosystem Services (ES) by regulating water availability (Elmhagen et al, 2015 ; Cowles et al. 2018). Understanding the relationship between vegetation and soil is an important step in ecosystem management (Zhang et al., 2015; Tang et al., 2016). This study was envisaged to serve the purpose of filling the knowledge gap in landscape terrain, LULC and climate regulation ES to local human population and dependent wildlife (Mbanze et al., 2019b).

The miombo woodlands areas are particularly hydrology data-poor with most research there focusing on land use as well as carbon and fire dynamics while recognising water resources research gaps (Allan et al., 2017; Ribeiro et al., 2013). This study responds to the need to document specific evidence of the effect of LULC on water resources in the regional miombo ecosystem (CBD, 2010; Franklin et al. 2016). This remains a challenge in the face of climate change where mitigation efforts require information on the cause-effect relationship in the landscape. This study was considered useful to contribute knowledge on water availability as well as trends which is needed to inform sustainable environmental management.

CHAPTER TWO
LITERATURE REVIEW

2.1 Water resources and wildlife conservation in Northern Mozambique

Southern African region has climate characterized by a high degree of variability from tropical to semi-arid zones. In the semi-arid climate zones, the transformation of rainfall into river flow variability is as high (Yang et al., 2019a). The climate of Mozambique varies significantly with difference in the amount, timing, and frequency of rainfall events in the different regions (Relief-Web, 2019; USAID, 2013), The rainy season begins in December and ends in March; and this season contributes 60-80% of the annual rainfall (Ehrhart & Twena, 2006; IFAD & WFP, 2018). Annual average rainfall is higher in the northern side of the country than in the central and southern regions. In the northern region where the study area is located, the annual rainfall can exceed 1000 mm; and in the south it is usually around 500 mm (Ehrhart & Twena, 2006; World Bank, 2007)

Niassa Special Reserve (NSR) is a wildlife conservation area in Northern Mozambique famous for miombo woodland ecosystems. In wildlife conservation landscapes, water availability is needed for animal consumption, as habitats for aquatic animals; for seed germination and growth of vegetation. Landscape hydrology is expressed in classes of wetlands, hillslopes and valley areas; and these areas have unique rainfall runoff behaviours and river flow and thus different contribution to the river through processes of overland and sub-surface flow (Gharari et al., 2011a). These runoff contribution processes are dependent on topography, geology, land use and climate. Understanding these holds the key to identification of water resources management needs for ecosystems conservation areas. This is important knowledge in wildlife conservation areas for understanding habitats (Nakagawa, 2018; Pei et al., 2018). Sustainable water resources like forests,, lakes rivers and wetlands are of key value in wildlife conservation as water is a life requirement for animals (Huntsinger et al., 2017).

2.2 The need for LULC indicators of climate and water availability

Research on LULC influences on hydrological fluxes and water availability is drawing a lot of scholarly interest (Albalawneh et al., 2015; Ekness & Randhir, 2015; Epting et al., 2018; Said et al., 2021; Wang et al., 2020; Woyessa & Welderufael, 2021). Natural vegetation cover spatial and temporal distributions are indicators of water availability for ecosystems and people and this is important knowledge in river basin management (Castro et al., 2018; Sianga & Fynn, 2017; Timberlake et al., 2004). Land-use and land-cover (LULC) influence water balance in river catchments by contributing to factors of rainfall runoff, soil water storage and evapotranspiration (Liu et al., 2017). Biomass production in landscapes has been shown to have a positive relationship with water availability for dependent ecosystems (Brauman et al., 2014b; Brockerhoff et al., 2017). The nature and coverage of vegetation biomass coupled with variations in freshness give an indication of soil water availability in regions (European Commission, 2014; Goslee et al., 1997). Data on occurrence of mosaics of LULC in different geometric and spatial arrangements is necessary for sustainable water resources management especially under climate change and increasing land use change global pressures (Chisola, der Laan, et al., 2020; Hallema et al., 2016; Hokanson et al., 2020). Knowledge of vegetation-cover patterns and structure; and hydrologic connectivity is important understanding soil and groundwater systems in river water source areas (Hallema et al., 2016; IPCC, 2019; Yang et al., 2012). Spatial patterns in vegetation cover reflects environmental hydrogeology and this knowledge is important to understand water sources from an ecological perspective in water resources management (Clarke, 2009). Forested landscapes are prone to disturbances from local land use changes, extreme climatic events, wildfires, atmospheric pollution and invasive species which affect the provision of forest goods, and environmental services and functions (Mosseler et al., 2009).

Vegetation influences evapotranspiration (ET), soil water infiltration, surface water runoff as well as organic matter and soil moisture processes affect water availability in river basins (Luo et al., 2020). Increase or reduction in evapotranspiration and runoff in a landscape can be caused by LULC (Yang et al., 2012). Patches of LULC are indicators of environmental water availability and changes reflected in vegetation community succession (Goslee et al., 1997). Vegetation spatial pattern characterization in a landscape is important in environment management to understand the connectivity of locations (Peters-lidard et al., 2017).

Degrading activities of LULC such as deforestation or agricultural intensification cause biodiversity changes and this is often manifested in species richness and abundance alterations (Jung et al., 2019). Environmental impacts of LULC are often exacerbated by human population growth in river basin and this causes changes and losses of ecosystems (Butsic et al., 2015; Jhariya & Raj, 2014). Information on changes in spatial pattern of vegetation cover in a landscape is key in environmental management to understand conservation needs for dependent ecosystems in an area (Peters-lidard et al., 2017). Uncertainty in vegetation landscape cover dynamics and atmospheric weather water cycle factors mean an uncertain future which is a concern for environmental management scientists (Sheil, 2018).

The ecosystems' capacity to provide services for mankind can be constrained by changes in the environment by factors including climate and human land use (Grizzetti et al., 2016; Haines-Young, 2009). Changes and dynamics of LULC have been identified as an environmental challenge that needs more research in land-atmosphere interfaces (Pan et al., 2017). Ecosystem changes and drivers as well as LULCC research is necessary data to provide knowledge for decision making in integrated water resources management in river basins (Clarke, 2009). Full understanding of land-cover influence on hydrological processes in a landscape requires comprehensive spatial analysis of LULCC across topographic divides in the context of climate of an area (Gao et al., 2018a). Vegetation ecosystems patterns represent factors of soil water, climate and soil hydraulic properties in landscape patches (Dirnböck & Grabherr, 2000b; Jiang et al., 2004; Muñoz-villers et al., 2011).

A landscape approach is required for managing vegetation cover in an area and this partly requires quantification of composition, structure and spatial dynamics of vegetation cover (Sayer et al., 2017)). A landscape mosaic approach is useful for LULC analysis in landscapes that have spatially heterogeneous mosaics of patch types over time (Lagro, 1991; Tello et al., 2020). Research has shown that vegetation study on Leaf Area Index (LAI) in NSR shows potential soil water variability in landscape hydrology (Ribeiro et al., 2008b). There was reported vegetation difference in hydrologic characterization of Dambos which are dry season water points in NSR (Mbanze et al., 2019b). Given the fact that NSR has human settlements areas, this calls for a thorough understanding of LULC and the implications for wildlife conservation and people. Climate and change effect on water availability in NSR and regional miombo ecosystem remain unknown with a need to document specific evidence (Franklin et al., 2016).

2.3 Land use and land cover characterisation for environmental management

Land use and land cover heterogenic units play complementary roles in modifying the river flow regime and knowledge of their complementarity is important in land use planning for water resources protection in river catchments (Hlásny et al., 2013; Raihan & Haroon, 2016). Knowledge of LULC hydrologic connectivity is important for planning conservation zones as well as integrated water resources management (Hallema et al., 2016; Barbosa et al., 2020; Yang et al., 2012). Landscapes mosaics of LULC occur in different geometric and spatial arrangements and this is necessary information for sustainable water resources management especially under climate change and increasing land use change global pressures (Chisola, der Laan, et al., 2020; Hallema et al., 2016; Hokanson et al., 2020).

Knowledge of vegetation-cover patterns and structure; and hydrologic connectivity is important for understanding soil water influences on vegetation ecosystems (Hallema et al., 2016). Forested landscapes are prone to disturbances from local LULCC, extreme climatic events, wildfires, atmospheric pollution and invasive species which affect the provision of forest goods, and environmental services and functions (Clarke, 2009). Spatial patterns in vegetation cover can reflect environmental wetness and this knowledge is important knowledge to understand resilience and habitats from a landscape ecology perspective (Yang et al., 2012).

It has been identified that LULC change is an environmental management challenge and environmental management needs more research in land-atmosphere interfaces in environmental planning (Pan et al., 2017). Landscape hydrology research that is focused on LULC is necessary to provide knowledge for integrated water resources management in river catchments because it shows storage and loss zones as well changes in water contributing areas (Brauman et al., 2007; Yang et al., 2012). Full understanding of LULC influence on hydrological processes in a landscape requires comprehensive spatial analysis across topographic divides (Asbjornsen et al., 2011). Natural vegetation spatial patterns represent factors of soil water, stream flows and groundwater in landscape LULC patches (Dirnböck & Grabherr, 2000a; Jiang et al., 2004; Sayer et al., 2017). A landscape approach is required for managing green landscapes and this depends on rigorous quantification of the composition and structure and spatial dynamics (Tello et al., 2020). A landscape mosaic approach is useful for LULC analysis in landscapes that have spatially heterogeneous mosaics of patch types over time (Lagro, 1991).

Vegetation influences Evapotranspiration (ET), soil water infiltration, surface runoff as well as organic matter and soil moisture processes and functions in river catchments (Mackey et al., 2009). LULC changes can have increase or reduction impacts on ET and runoff (Lu et al., 2015; Yang et al., 2012). Vegetation cover patches on a landscape are indicators of environmental water availability reflected in biomass production and vegetation community succession which is important knowledge for understanding river water contributing areas and monitoring hydrological changes (Luo et al., 2020). Vegetation spatial pattern characterization in a landscape is important in environment management to understand connectivity of locations (Gao et al., 2018a). Landscape heterogeneity is also shown in spatial vegetation patterns which are dependent on water availability because topographic gradients influence soil water storage in a river catchment and are influential in vegetation growth patterns (Gao et al., 2018a). LULC change leading to deforestation or agricultural intensification is a key driver of biodiversity changes manifested in species richness and abundance alterations (Jung et al., 2019).

Biomass production in landscapes has been shown to have a positive relationship with water availability in existing ecosystems (Brauman et al., 2014a; Brockerhoff et al., 2017). Any LULCC resulting in biomass reduction in landscapes negatively affect water balance in river basin (Liu et al., 2017). Natural vegetation cover spatial and temporal distributions are indicators of environmental water availability and this is important knowledge in river basin management (De Castro Nunes Santos Terra et al., 2018; Sianga & Fynn, 2017). The nature and coverage of vegetation biomass coupled with variations in freshness give an indication of soil water availability (European Commission, 2014; Goslee et al., 1997). Mosaics of LULC occur in different geometric and spatial arrangements and this is necessary information for sustainable water resources management especially under climate change and increasing land use change global pressures (Chisola, Laan, et al., 2020; Hallema et al., 2016; Hokanson et al., 2020). Spatial patterns in vegetation land cover reflects environmental hydrogeology and this knowledge is important to understand water sources from an ecological perspective (Clarke, 2009). Vegetation influences evapotranspiration (ET), soil water infiltration, surface runoff as well as organic matter and soil moisture processes and functions in river basins (Luo et al., 2020). Vegetation spatial pattern characterization is important in landscape based in environment management to understand connectivity of locations (Peters-lidard, Clark, Samaniego, Verhoest, Emmerik, et al., 2017). Heterogenic units play complementary roles in modifying the water regime and knowledge of their complementarity is important in water resources management in river basins (Hlásny et al., 2013; Raihan & Haroon, 2016). Landscape heterogeneity is also shown in spatial vegetation patterns which are dependent on water availability. Topographic gradients define water storage in a river catchment and are influential in vegetation growth patterns (Gao et al., 2018b; Nyman et al., 2013).

Changes in LULC such as deforestation or agricultural intensification is a key driver of biodiversity changes manifested in species richness and abundance alterations and all these are threats existing in Incalaue catchment (Jung, 2019). Environmental impacts of LULC are often exacerbated by human population growth in river basin where they exist (Butsic et al., 2015; Jhariya & Raj, 2014). Information on changes in spatial pattern of vegetation cover in a landscape is key in environmental management to understand the connectivity within ecosystems (Peters-lidard, Clark, Samaniego, Verhoest, Van, et al., 2017). Heterogenic units play complementary roles in modifying the water regime and knowledge of their complementarity is important in water resources management in river basins (Hlásny et al., 2013; Raihan & Haroon, 2016). Presently, the world is experiencing climate change as well as LULC effects resulting from population pressure; and this has effect on vegetation which can be a challenge in wildlife conservation areas. Uncertainty in vegetation landscape cover dynamics and atmospheric weather water cycle factors mean an uncertain future in environmental management (Sheil, 2018).

2.4 Conservation landscapes and water availability management

Natural ecosystem structure is driven by processes of biogeochemical transformations; paedogenesis; and water availability linkages (Hofmeister et al., 2019). Biomass production in landscapes has been shown to have a positive relationship with water availability for dependent ecosystems (Brockerhoff et al., 2017; Brauman et al., 2017). The potential of a landscape to have vegetation and provide related ecosystem services is dependent on environmental water availability to support biological growth under suitable geological and climatic factors (Brauman, 2015; Gebrechorkos et al., 2018; Hou et al., 2018). Landscapes hydrology aspects of topography, soils, and climate determine and vegetation structure; and water availability influences biomass production (Zhang et al., 2015 ; Xu et al., 2016).

Quantifying characteristics of landscape environmental fluxes is important for determining appropriate scales for water resources management. Scale classification of water resources in a landscape is important in environment management to understand relative importance and connectivity (Peters-lidard, Clark, Samaniego, Verhoest, et al., 2017). Heterogenic units play complementary roles in modifying the water regime and knowledge of their complementarity is important in water resources management in river catchments to derive conservation needs (Hlásny et al., 2013; Raihan & Haroon, 2016).

Understanding river flow regime and contributing areas is important in land use planning to determine conservation options to safeguard water sources. Landscape hydrology is reflected in vegetation cover as well as soil and slope factors; and it is ideal that these are investigated simultaneously in assessment of river behaviours (Weiguang & Fu, 2020; Istanbulluoglu & Bras, 2005; Istanbulluoglu et al., 2004). Integrated water resource management is vital for natural ecosystems conservation and human societies (Chen et al., 2022; Falkenmark, 2014; Piralizefrehei & Fisher, 2022; Tadesse et al., 2015; UNEP, 2021).

Nature's design and ecological behaviour are affected by land use and landscape planning; and it is important to consider influence, especially in recent times given the increasing human interaction with the natural environment (Imran et al., 2014). Several landscape science studies have recommended research on landscape hydrology and determinants considering that land use patterns are determined by natural factors of climate, geology and soils whose interaction and human disturbance put sustainability of ecosystems services provision in jeopardy (Borrelli et al., 2020; Franch-pardo & Napoletano, 2017).

In conservation areas, animal consumption of water; water habitats for aquatic animals; seed germination in wet soils; growth of grass in wet landscape areas; and supporting vegetation growth are some of the ecosystem water needs in conservation areas. Landscape hydrology is expressed in classes of wetland, hillslope and plateau; and these have dominant rainfall runoff and river flow contribution through processes of saturation excess overland flow; and storage excess sub-surface flow (Gharari et al., 2011b). These are dependent on topography, geology and land use; and these hold the key to identification of landscapes ecosystems conservation in integrated water resources management. This is important in knowledge in wildlife conservation areas for a landscape-ecology-based approach to conservation (Nakagawa, 2018; Pei et al., 2018).

Sustainable water availability is key value in wildlife conservation as water is a life requirement for animals (Huntsinger et al., 2017). Environment degradation of wildlife conservation areas causes to shifts in relative abundance of flora and fauna diversity (Pei et al., 2018). Choices of wildlife habitats are influenced by water availability in a landscape (Alho & Silva, 2012; Huntsinger et al., 2017; Sianga & Fynn, 2017; Tshipa et al., 2017); and therefore quantifying land use and land cover is important in water resources management to ensure water availability in a conservation area. This means that conservation objectives cannot be easily achievable where therewith lack of understanding and management needs to support water availability in the river catchment in the LULC perspective.

Vegetation wetness variability as was shown in Leaf Area Index (LAI) in NSR (Ribeiro et al. 2013), which shows variability in underlying hydrologic processes. There is also vegetation difference in hydrologic characterisation zones of Dambos (Mbanze et al., 2019a). This calls for understanding landscape hydrology and implications for conservation both with regard to habitat environmental security for dependent wildlife; and water availability for people. Assessment of the above dynamics calls for understanding of the complex interaction between intrinsic and external factors that drive water availability. Eco-hydrology understanding is important to support ecosystem conservation efforts to avert a water stress situation occurrence and its detrimental impacts.

2.5 Modelling of micro-catchments in data-poor environments and scalability

Modelling of landscape rainfall runoff to determine amounts and contributing areas is useful to for inform LULC planning; and environmental management as it offers information on river water temporal dynamics (Chen et al., 2020; Istanbulluoglu et al., 2004; Istanbulluoglu & Bras, 2005a).

Understanding factors that influence rainfall and river flow relationship in river catchments is important to estimate environmental management needs to sustain water availability (Fereydan et al., 2019). Conservation ecologists in wildlife areas require knowledge of spatial distribution of these factors that influence water availability and impacts in animal habitats in ecosystems (Allen & Singh, 2016). Modelling river flow dynamics and control factors is important to understand river flow changes at spatial and temporal scales (Cuo & Zhang, 2013; Lu et al., 2015).

Many river catchments in semi-arid areas in developing countries suffer from limited data availability and process knowledge (Aboumaria, 2020; Love et al., 2011; Nejadhashemi et al., 2011). Detailed studies that collect data on river discharge and other hydrological characteristics of small ungauged catchments are of benefit for water resources management as well as for hydrological science research agenda in wider and neighbouring river catchments (Sivapalan et al., 2003). One approach to address these challenges of river flow uncertainty in is catchments is regionalisation, which provides methods which makes intensive valuable detail informed understanding of hydrological process for scaling to understand wider areas(Osei et al., 2017; Pandey et al., 2021).

Hydrologic modelling has been applied in many parts of the world at various spatial and temporal scales; and environmental conditions and to predict land use/cover and change impacts on water availability (Osei et al., 2017; Pandey et al., 2021; Tudose et al., 2021; Wu et al., 2021). Semi-distributed models like Soil and Water Assessment Tool (SWAT) can be used at small watershed scale in ungauged catchments to predict water yields for different LULC classes and soils combinations. The model was chosen for this study because of its high adaptability to investigate a wide range of related parameters in river catchment and flexibility with auto-calibration in ungauged catchments (Amatya et al., 2011; H. Mishra et al., 2017; Näschen et al., 2018; Tudose et al., 2021).

Hydrologic modelling is useful to investigate rainfall runoff relationships for water resources planning and management (Osei et al., 2017; Pandey et al., 2021; Tudose et al., 2021). Quantifying characteristics of landscape environmental fluxes is important environment management to understand relative importance and connectivity of water source areas (Peters-lidard, Clark, Samaniego, Verhoest, Van, et al., 2017). This is important in wildlife conservation areas to protect river source areas which is important for dependent fauna in conservation areas (Murray-Tortarolo et al., 2017; Wilson et al., 2017).

Modelling studies in this research were conducted using SWAT model which has been proven to work in the area in a nearby but bigger Rouvuma catchment (Minihane, 2012). This was chosen in attempt to use understanding of the internal catchment processes and hydrologic pathways to further test the model using another satellite climate data (Sidle, 2021). The model is based on a concept that rainfall may be intercepted and held in the vegetation canopy or fall to the soil surface where it will infiltrate and move downslope or is stored as groundwater; or flow overland as runoff. The hydrological cycle that is simulated by SWAT is based on the water balance equation (3):

$$SW_t = SW_0 + \sum_{t=1}^{t} (R_{day}(i) - Q_{surf}(i) - E_{sub}(i) - w_{seep}(i) - Q_{gw} \quad (3)$$

where SW_t is the final soil water content (mmH2O), SW0 is the initial soil water content on day i (mmH2O), t is the time (days), R_{day} is the amount of precipitation on day i (mmH2O), Q_{surf} is the amount of surface runoff on day i (mmH2O), E_{sub} is the amount of evapotranspiration on day i (mmH2O), w_{seep} is the amount of water entering the vadose zone from the soil profile on day i (mmH2O), and Q_{gw} is the amount of return flow on day i (mmH_2O).

In rainfall runoff modelling, SWAT model was chosen because it was the only model that could be used for understanding catchment rainfall runoff behaviour since it has been used in a nearby Rouvuma catchment (Minihane, 2012) using short term collected data and remote sensed. This study assessed applicability of remotely sensed data for river flow modelling rainfall runoff using SWAT model The model performance for the river Rouvuma catchment was as show below;

- Nash-Sutcliffe Efficiency ratio of 0.8,
- An efficiency ratio based on mean historical streamflow by month of 0.6,
- An efficiency ratio based on inverse flows (sensitive to low flows) of 0.9, and
- A coefficient of determination equal to 0.99.

SWAT model has been proven to work without on-site calibration and basing on performance of the model in neighbouring catchments to model shown to be helpful for ungauged catchments (Pontes et al., 2016; Roth et al., 2016). In that context, the modelling approach of this study was to use the successful model performance for the Rovuma river catchment as a basis to adopt for use in Incalaue river catchment. The performance of the model for Ruvouma was classified as very good in the monthly time step and acceptable for the daily time step.

2.6 Theoretical framework

Integrated water resource management and conservation of sources of freshwater is vital for natural ecosystems conservation and human societies amidst land use and climate pressures in the world today (Chen et al., 2022; Falkenmark, 2014; Piralizefrehei & Fisher, 2022; Tadesse et al., 2015; UNEP, 2021). Landscape approach to water resources management research is increasingly drawing scholarly attention to understanding land use and land cover factors influencing hydrological fluxes and environmental response in a changing environment (Albalawneh et al., 2015; Ekness & Randhir, 2015; Epting et al., 2018; Said et al., 2021; Wang et al., 2020; Woyessa & Welderufael, 2021). Research has in recent times focused on landscape components and patterns of ecosystems (relief, soil, biotic communities) and human influences; and spatial and changes (Ceradini et al., 2021; Chisola, der Laan, et al., 2020; Delclaux & Depraetere, 2001; Gann & Childers, 2006; Prokopová et al., 2019).

The study was built on the theory that habitat corridors provide connectivity in wildlife conservation areas (Beier & Noss, 1998). The theorists define the wildlife-corridor areas to include "non-habitat" or "the portion of the landscape in which habitat patches and corridors are embedded. It was argued by the theorists that land use planning should capture the myriad land cover types and functional environmental continuum exist in the wildlife corridors. Recent research has shown that integrated water resource management and conservation of natural ecosystems amidst land use and climate pressures in the world today (Chen et al., 2022; Falkenmark, 2014; Piralizefrehei & Fisher, 2022; Tadesse et al., 2015; UNEP, 2021).

The study also inclined to a proven hypothesis that human society and land use development follow environmental transformation, in terms of the physical geography of a place (Mikesell, 1992). The above theorist cited an earlier theory by Johnston (1978) which hypothesized that patterns of residential segregation of components in urban socio-spatial structure (cf. social area analysis) are influenced by ecological factors in small areas within cities. The roots of the above theory have been linked back to works of ancient Greek scientists such as Hippocrates and Aristotle who linked the characteristics of people in certain places to be influence by environmental factors in climatic zones (Briassoulis, 2020). This inclination was made to understand and explain human land use traits and discuss inherent risks.

Natural design and ecological behaviour are affected by land use and landscape planning; and it is important to consider environmental determinism's influence especially in recent times given the increasing humans interaction with the natural environment (Imran et al., 2014). Several other landscape science studies have also adopted the environmental determinism theory considering that land use patterns are determined by natural factors of climate, geology and soils whose interaction human disturbance put sustainability of ecosystems services provision in jeopardy (Borrelli et al., 2020; Franch-pardo & Napoletano, 2017). The parameters chosen for this study was based on the above theory to capture water resources availability and land use in a dry season wildlife corridor Incalaue catchment.

2.7 Conceptual framework

The research was conceptualised to assess the factors and linkages that that affect water availability in respect of LULC in the miombo woodland ecosystems (Figure 6). The study used rainfall that was gauged as an overall representation of climate contribution to surface water that was later translated into river flow under influenced by LULC, soil and slope factors.

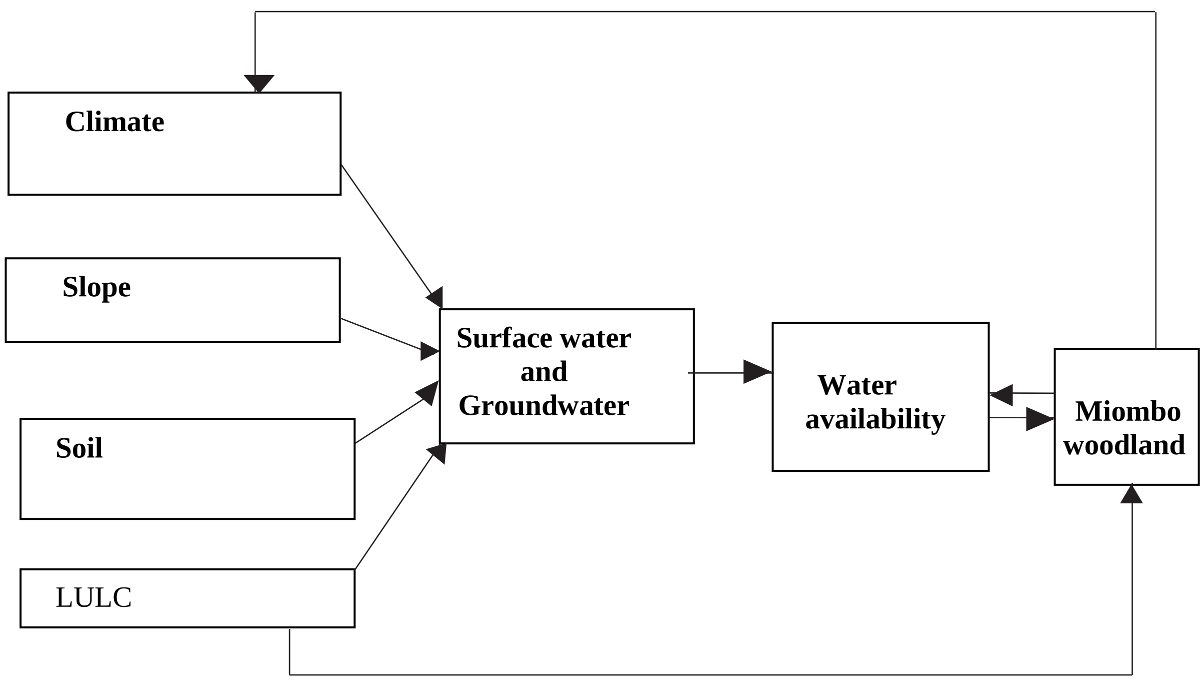

Figure 6: Conceptual framework of the study

CHAPTER THREE

METHODOLOGY

3.1 Methodological framework

Surface water availability contribution by rainfall in a river catchment depends on amounts received and is influenced by LULC (evapotranspiration and water harvesting), slope and runoff to rivers and losses through soil water infiltration and groundwater recharge. River flow response to rainfall is an overall representative of climate effects on water balance in a river catchment which partly is influenced by the soil-vegetation relationship naturally. It is important to study baseline situations of LULC, rainfall, slope and soil properties to explain rainfall and river flow relationships. Rainfall contribution to water availability can be in form of river water and groundwater recharge which is dependent on geology/soil and slope factors. It is important to study these determinants of water availability as a combination to draw scientific conclusions and make recommendations and ensure their sustainability (Figure 7).

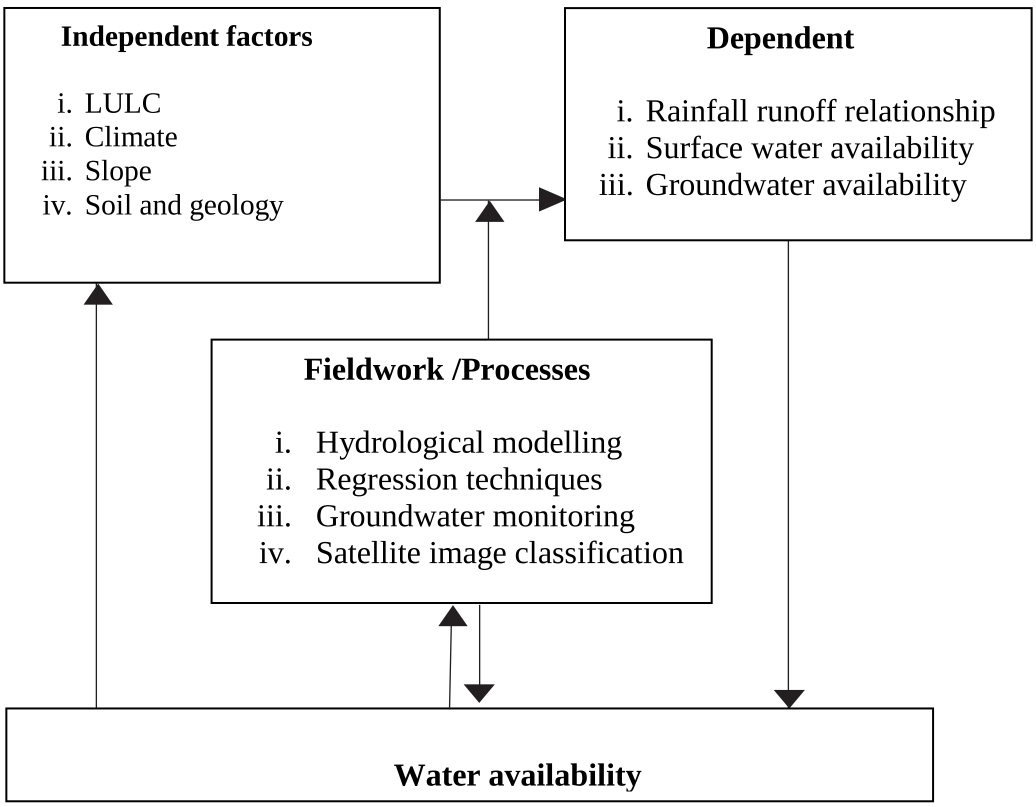

Figure 7: Methodological framework

3.2 Data collection

The study involved the collection of secondary and fieldwork data. Fieldwork commenced in September 2019 and data collection activities were done until May 2021.

3.2.1 Physical data collection

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3.2.1.1 Rainfall and river flow

Three rainfall stations were installed with one in Ntimbo 1 village; Lisongole village; another at Mbatamila camp while a river flow gauging station was set up at the bridge crossing point of the Mecula – Marrupa road (Table 2). Data was collected from November 2019 to May 202). Data at river gauging station and rainfall stations all recorded data between 8:00am and 9:00am each day. Personally I recorded the data and when not available or unable to travel to the field, research assistants would collect the data. Field assistants had to be people who can read and write preferably located not far from the river and these were available for research data collection locations. Field assistants were trained for 4 weeks in everyday measurement routines before they got notebooks to start working independently where needed.

Table 2: Location of river gauging stations

Location	**Coordinates**
Mbatamila rainfall station	37L 341973.22 E; 8654176,44 S
Ntimbo 1 rainfall station	37L 354364.78 E; 8643087.78 S
Lisongole rainfall station	37L 353802.67 E; 8635035.11 S
Incalaue river gauging station	37L 353920.86 E; 8637556.09 S

3.2.1.2 Vegetation classification data

Potential specific representative areas for different land use/cover classes were identified using rectified and geo-referenced google satellite image of the catchment area in ArcGIS 10.5 software. Onscreen digitizing of polygons containing homogenous areas of vegetation reflected in the images was performed. Polygons of 50m x 50m containing homogenous areas of vegetation for different land-cover classes were selected using geo-referenced google satellite images in ArcGIS 10.5 software. Onscreen digitization of these google images was used to independently selected location points and confirm vegetation cover class in those polygons. Each polygon was divided into 25 plots of 10m x 10m. One of the plots of 10m x 10m representative of vegetation description above was selected in an accessible location. The wider 50m x 50m and subdivisions of 10m x 10m was done to maximise chances of getting representative vegetation using probability sampling. In selection of study plots, chance was ensured by randomly choosing one plot from the 25 plots. If a chosen plot was inaccessible for vegetation sampling, the nearest accessible one was chosen.

Two survey polygons were available for other classes but only one for wetland as this area was very risky in both dry and wet season due to wildlife. During fieldwork, tracking to sites for laying plots for vegetation survey plots in vegetation classes was done by GPS (Garmin eTrex) which has ~3m accuracy. Field data was collected in November and December 2009 for end of dry season and in April and May 2020 for end of the wet season. The end of seasons sampling was done to fully characterise vegetation.

In preparation for LULC classification, a total of 17 location points were chosen with 60% of this as training points; and 40% as a validation points. In total, 10 points were used for training and 7 for validation (Figure 8). The 10 location-points included 2 points for each vegetation class except wetland. Additionally, two plots were chosen for impediments and burned area/settlement as point non-vegetation classes. The non-vegetation land use and land cover classes were thus also verified and also shown on maps. During image classification, training data collection, the total number of tree and shrub stems were counted. Counts were made of the total number of tree stems >0.5 m in height and stem wood <3cm in the 10 m^2 quadrats (Dile et al., 2013).

The area experiences harsh dry season which involve most vegetation shedding leaves. In selected plots, sampling during standing dry stems were counted in the dry of were visited in the wet season (again, subject to accessibility) to confirm if the vegetation there had fresh leaves and nature of vegetation thickness (field based classification). Counts of plants and density were not made because of the closed nature of woodland vegetation in a wildlife area. Fieldwork was done in November and December 2019 for the dry season and April to May 2020 after the wet season. Identification of sites was done visually while walking through the reserve to target class representative points (Merwe & Hoffman, 2019).

The survey plots were available for other classes but only not for wetland as this area was considered very risky in both dry and wet season due to wildlife (Figure 8).

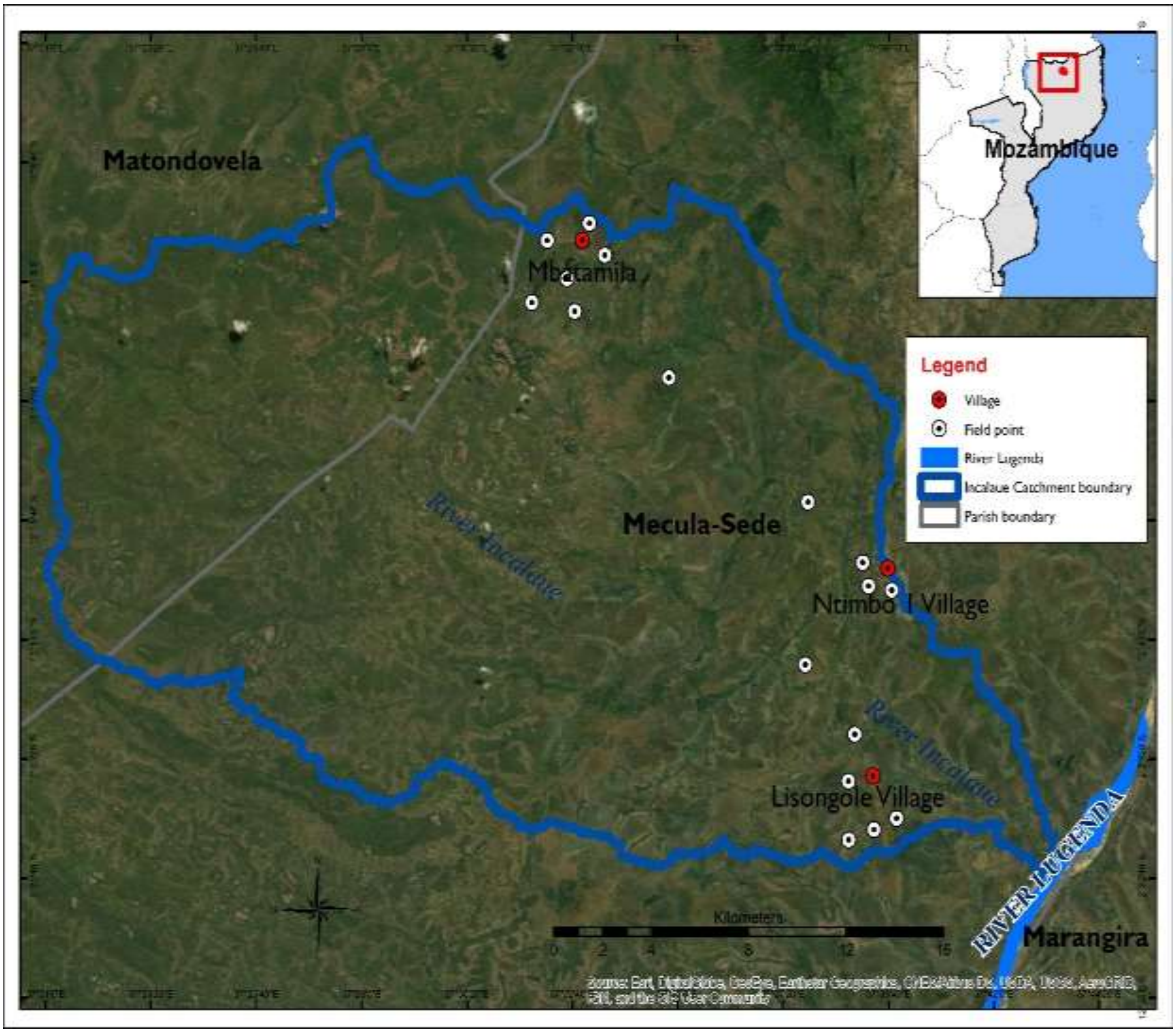

Figure 8: Land use and cover classification field data collection points (GCPs)

In each sampled plot, all vascular plants present were recorded; and canopy cover estimated. Access to sampling sites was done by GPS tracking (*Garmin eTrex* which has ~3m accuracy) and if a chosen point. Field data was collected in November and December 2009 for end of dry season and in April and May 2020 and verification sampling was again randomly done in October 2020 and May 2021, at the end of the dry and wet season respectively.

3.2.1.3 Soil data

Soil classification and water holding capacity assessments were done in vegetation zones. During fieldwork, soil samples were collected at the centre of the geo-referenced 50m x 50m plot that was used for vegetation classification. The samples were coded for vegetation classes as Low density woodland (A); Wooded grassland (B); Medium density wooded (C); Mountain forest (D); and Low density woodland (E) locations in Table 3 below). Sampling was designed to characterise soil properties up to 100 cm depth which has been reported to be the root zone for grass and shrubs in the area (Wolf & Menne, 2007). Data was also collected for characterisation of properties that contribute to water retention capacity up to 100cm depth. Soil samples were taken from surface to 100 cm at intervals of 20 cm and integrated for a sample.

Soil samples were taken to the laboratory at Eduardo Mondlane University in Maputo for laboratory analysis. Soils were analysed for particle size, bulk density, porosity, organic matter content, soil carbon content, sand content (%), clay content (%) and silt content (%). There parameters above were assessed to characterise soil water holding and retention properties which influence the amount soil moisture available for plants in a given soil. The relationship and backward-forward influences of bulk density, infiltration, rooting depth, available water capacity, soil porosity, plant nutrient availability, and soil microorganism activity are an indicator of soil health for supporting crop growth. Soil sample collection and laboratory analysis was done following the standard methods (Table 3).

Table 3: Soil assessment methods

Parameter	**Units**	**Method of determination**
Organic matter	%	Walkley & Black
Carbon	%	Walkley & Black
Sand, Silt and Clay	%	Robinson's method
Bulk density (dG)	g/cm3	pF ring method
Porosity (P)	%	P (%) = (1-dG/dP) *100
soil particle density (dP)	Kg/m3, g/cm3	pycnometer method

In the field, soils samples were picked using a hand auger up to the maximum reported 1 meter depth in the area and deeper up to 1.2 m where it was possible (Pienimäki, 2014). Where maximum sampling depth was not possible, the maximum affordable depth was used. The process at every site involved mixing of 3 soil samples of 10mg taken at 30 cm, 60cm and 100cm to determine physical and chemical factors that determine water storage potential within the shallow root zone (Groenendyk et al., 2015).

The approach was focused on differences that capture water storage potential influencing factors within the surface soil layer which represents the shallow root zone. The field based soil characterisation was also used to support digitization of the available hard copy soil texture map obtained from Instituto de Investigação Agrária de Moçambique (IIAM) which was used to show top soil textural classes to support FAO data derived soil map developed (Figure 3 above). Soil texture was examined in the field using the hand feel method (McGarry, 2004) to validate the available regional soil map in the catchment. This method involves adding drops of water to 2 table-spoonfuls of mixed soil sample held on the thumb with mixing until soil is mild-wet ensuring that no water dripping or soil being very wet and then pressing it into a ball shape. When the pressed and soil would stay as separated granules and formed a pyramid and no shape, it was taken as coarse texture; when it was sticky enough to form a weak ball shapes which would crack easily on drying as medium texture; and easy to form a firm round shape without showing cracks on drying as peaty soil (Table 4). Four samples would be taken from a sampling plot of one square meter area, taking and mixing samples from plot corners at points marked on vegetation classified map shown on Figure 8 above (Wulfson, 2010).

Table 4: Locations of soil sampling points

Vegetation class	Code	Location		Plot 1	Plot 2	Plot 3	Class taken
		X	Y				
Low density woodland	A	37.535	-12.170	Coarse	Medium	Coarse	Coarse
Wooded grassland	B	37.530	-12.190	Peaty	Medium	Peaty	Peaty
Medium density woodland	C	37.545	-12.193	Medium	Coarse	Medium	Medium
High density woodland	D	37.580	-12.215	Medium	Coarse	Coarse	Coarse
Mountain Forest	E	37.632	-12.255	Coarse	Coarse	Coarse	Coarse

3.2.1.4 Rainfall and river flow measurement

Three rainfall stations were installed with one in Ntimbo 1 village; Lisongole village; another at Mbatamila camp while a river flow gauging station was set up upstream of the bridge crossing the river on the Mecula – Marrupa road (Table 5). The stations were installed in November 2019 and data collected until May 2021. At river flow and rainfall gauging stations, data was recorded data between 8:00am and 9:00am each day. I personally recorded the data and when not available, research assistants would collect the data. Field assistants had to be people who can read and write, preferably staying near the gauging station. Field assistants were practically in measurement routines before they were given notebooks to start working independently.

Table 5: Rainfall and river discharge gauging stations

Location	Coordinates
Mbatamila rainfall station	37L 341973.22 E; 8654176,44 S
Ntimbo 1 rainfall station	37L 354364.78 E; 8643087.78 S
Lisongole rainfall station	37L 353802.67 E; 8635035.11 S
Incalaue river gauging station	37L 353920.86 E; 8637556.09 S

3.2.1.5 Groundwater yield measurement

In this study, groundwater springs catchments were delineated based water yield stream flow pour points into the river. The spring catchments were delineated based on topographic/landscape drainage to assess their LULC and soil contribution to surface water availability.

The identified springs were gauged to determine their flow rate in seasons to estimate rainy season contribution. The measurements were done for 1 month each at peaks of the dry season (August - November, 2019); and wet season (February - March, 2020). The measurements were made for 20 minutes and 3 times in a day at intervals of 4 hours (at 8:00 am, 12:00 am and 4:00 pm). The measurements were made during day time because of wildlife risk but still every day, of 3 measurements were done.

3.2.2 Interviews

Historical rainfall and river flow data was needed while the catchment is not gauged. Therefore a method of environmental change community memory based tracking of trends was deployed (Alessa et al., 2016; Danielsen et al., 2022; Fraisl et al., 2022; Houde et al., 2022; Van Bavel et al., 2020) Local people in communities were consulted for memory of changes and trends of the study parameters which included history of rainfall and river flow seasons as well as water availability and access in the dry season; groundwater springs yield.

The estimated number of households was 56 for Lisongole and 67 for Ntimbo 1. Community consultative meetings were held with all household heads who had stayed in the area for >30 years. This allowed voluntary attendance of meetings by majority community members in the category and care was taken to ensure that all households were informed. Attendance of these meetings was by 33 (49.3%) of household heads in Ntimbo 1 and 38 (67.9%) in Lisongole. The community meetings were later supplemented by single interviews with a village leader and 3 people >60 years who had stayed in the area also for >40 years. These 3 other people in addition to the community leader were interviewed separately in assumption to maximise the chance that they single mid-set relaxed reflection and good track memory even before study time and as mature people they could inform the study better by sitting with me to have focus and deeper discussion on the changes.

Attendance of the community consultative meetings was by 33 household heads in Ntimbo 1 and 38 in Lisongole; and these were meetings held timing in the afternoons when people are not in gardens. In consultations, answers would be collected in voluntarily from the participants in the open and others asked to choose what they agreed. This was because the study targeted historic variations of the parameters that benefit from shared memories.

Interviews were held in the dry season timing in the afternoons when people were not in the gardens. This approach of opening up household interviews by using simple random sampling and selecting any available adult member was used to avoid bias while ensuring efficiency by sampling adults with experience in the area (Kondo et al., 2014). The closeness of communities that use the river at similar points ensures data reliability and further enhances historical data reliability.

3.3 Land use and land cover classification

3.3.1 Satellite data processing

Mapping of LULC and analysis of LULC change was conducted using Remote Sensing (RS) and GIS (Geographical Information System). The study used sample images at decadal scale (best images were for 2001, 2009 and 2021) to assess LULCC with an objective of assessing vegetation cover change to detect indicators of landscape hydrology. The study used satellite images of 15m x 15m spatial resolution sharpened from the freely downloaded 30m × 30m by merging spatial data in the high-resolution panchromatic bands with colour information in the multispectral bands using the nearest neighbour diffusion pan sharpening technique to create a higher resolution colour image that improves mapping and classification accuracy (Alawamy et al., 2020). This was because the high-resolution Landsat imagery datasets could not be accessed for all the study years. The images were targeted between May and July at the start of the dry season) when the sky is mostly clear were used. Two images were secured for July in the mid-season (2009 and 2021) and the other one 2001 was for June (which is the same range). Initially, a satellite image of 20219 was used for fieldwork planning and the study finally used the image of 2021 for final assessment for fear of changes since 2021 is 2 years after 2019 and LULC can change. Landsat satellite images were used for this study. The images were downloaded from USGS website http://www.earthexplorer.usgs.gov/ (Accessed 18th June 2019; and 22nd September 2021).

These initial satellite images used were therefore Landsat-7 EMT+ (2001); Landsat-5TM (2009); and Landsat-8 OLI for 2019 (Table 6. The criteria was to select a satellite image that would meet the cloud cover limit set at <20%. Thid cloud cover limit was set because the areas largely has cloudy images. The choice of the different Landsat classes was made to maximise LULC mapping in the area. Landsat 8 which is widely believed to the best vegetation mapping satellite image started (Available from February 11, 2013) was not possible for the year 2001 and Landsat 7 EMT+ was used. A good cloud free Landsat 8 image considering the limit could not be identified exactly for the area in 2009 so as an alternative, good vegetation mapping satellite image (Landsat 5 TM) was used.

Table 6: Satellite images used

Year	Satellite/Sensor	Date	Path	Row	Band No.	Resolution (m)
2001	LE07166069200111080IT1-SC20190923094509.tar	2001-6-08	166	069	321	30
2009	LT05_L1TP_166069_20090717_20180620_01_T1.tar	2009-07-17	166	069	432	30
2021	LC08_L1TP_166069_20210713_20190719_01_T1.tar	2021-07-13	166	069	543	30

Haze Reduction Procedure based was used based on Tasseled Cap Transformation Algorithm on our Landsat images. Exclusion masks were put on "no-data" areas for the images with high haze content or compact clouds (> 10). At the end of this stage, I obtained a set of normalized multiband images and RGB (Red, Blue and Green) composites. The usable band numbers for RGB viewing were 4, 3, 2 for 2019 and the same for 2009; and 3, 2, 1 for 2001 as given above. Image classification was done in ArcGIS 10.5 and ENVI 5.1software version. The data processing steps included image acquisition, pre-processing and classification. Supervised image classification was verified using Google reference and ground truthing data from the field (section 3.2.1.2 above).

Radiometric correction of images was done in ENVI 5.1 where raw data from the sensors (DNs) were converted to top-of-atmosphere reflectance. The images were atmospherically corrected using Dark Object Subtraction procedure to minimize the atmospheric impact on the sensor (Allouche et al., 2018). Geometric correction of the Landsat-8 OLI (2019) image was done using the field data collected from Ground Control Points (GPCs) taken at a scale of 1:50,000 provided the basis for the 2001 and 2009 image-to-image registration (Santos et al., 2019).

The study benefitted from use of Landsat-5TM image for 2009 as this avoided the effect of those missing data in 7 ETM+ for this year due to SLC (Scan Line Corrector) failure from 2003 till 2013 that would result in data losses (Santos et al., 2019). There is slight passable error in Landsat-5 TM in some applications, such as monitoring land use change and crop quality but this does not significantly affect classification for our purpose (Haque & Basak, 2017).

The resolution of Landsat-8 OLI imagery and Landsat-7 ETM+ was sharpened from 30m to 15 m by merging spatial data in the high-resolution panchromatic bands with colour information in the multispectral bands using the nearest neighbour diffusion pan sharpening technique to create a higher resolution colour image that improves mapping and classification accuracy

(Santos et al., 2019). Given that panchromatic band is not available for Landsat-5 TM image captured in 2001, we also resampled data from 30 to 15 m using the nearest neighbour technique to ensure consistency with OLI and ETM+ data used for other years in this study (Santos et al., 2019).

3.3.2 Image Classification

Image classification was done using algorithms in ENVI software version 5.1 for spectral reflectance clustering to determine land-cover spectral classes for the catchment delineated (Tilahun, 2015). Sub-catchments separation and labels thereafter are default generated by FID. The images were atmospherically corrected using Dark Object Subtraction procedure to minimize the atmospheric impact on the sensor (Hernández-Stefanoni & Dupuy, 2007). Dark Object Subtraction is an empirical atmospheric correction method for satellite imagery used to bring out the pixels that are hidden in complete shadow (Abdelkareem et al., 2018). Dark Object Subtraction procedure minimizes the atmospheric impact on the sensor (Schroeder et al., 2006). This method searches and removes dark pixel values. The point-based classification was used to map land use land use/ (Santos et al., 2019).

Two methods were used to classify the composite images and Iso-Cluster unsupervised classification was done and maximum likelihood classification used to create a classified raster output (Hernández-Stefanoni & Dupuy, 2007). The combination of supervised and unsupervised classification was used for land use/cover mapping to confirm accuracy of classification of mapping where possible and make informed decision where only unsupervised classification was possible.

Emphasis was placed on zoning vegetation classes to capture the beta diversity (capture in great detail) within the study area (Tan et al., 2017). The objective at this stage was to classify vegetation into groups sharing similar floristic structure using satellite images. This is based on reflectance values of satellite imagery mapped land cover types (Hernández-Stefanoni & Dupuy, 2007). Images captured between June and July (towards the middle of the dry season) when vegetation is representative of classes given the area has strong wet and dry seasons. This is the time when vegetation is clear excluding flush and vegetation. To collect vegetation data in the field, ancillary data used were gotten from Ground Control Points (GCP) and topographic map at a scale of 1:50,000. Using Landsat-8 OLI for 2019 which was luckily at the start of the study. The study used the composite images was used to select suitable "training'' which are vegetation cover data collection plots for the different land cover types (Cingolani et al., 2004). In choosing of training sites, chance was ensured by selecting three site options for every class at representative accessible locations and randomly choosing two at accessible locations (Figure 6 above). Identification of sites for laying plots (field points) in vegetation classes was done by tracking to a location using a GPS. Field data were collected in November and December 2009 for end of dry season and in April and May 2020 for end of the wet season. The end of seasons sampling was done to fully characterise vegetation species composition.

3.3.3 Classification accuracy assessment

After image classification, before proceeding with output data usage, accuracy was tested using Kappa statistics (Abdelkareem et al., 2018; Tilahun, 2015). This method is used to compare classified images with ground truth data and is an important component of land use land cover classification accuracy in land use/cover analysis. A confusion matrix was then used to evaluate whether an image is correctly classified or not. The data used for validation also known as Referenced data sets (ROIs) were collected from randomly selected point locations in the classified vegetation map for each LULC class. This is an overlap-area-based zonal statistics table for testing mapping of reference sample polygons or points; so a choice of using points was made (Fichera et al., 2017; Rwanga & Ndambuki, 2017).

The use of reference point for classification accuracy assessment was used in order to maximize the chances of accessing many areas and because the area is a wild reserve this minimizes risk by being at a place for a short time. Reference points for classification accuracy assessment were randomly selected using the best guess approach to enable use of independent data collection (Millard & Richardson, 2015). Access to selected points was guided by local people because of the difficult terrain and inherent risks in the catchment.

Kappa statistics analysis was performed using the formula below (Equation 1). The choice of using google Earth image was made because of the need to compare image captured in 2021 with those from the other two years (2001 and 2009).

$$K = \frac{N\sum_{i=1}^{r} x_{ii} - \sum_{i=1}^{r}(x_i + x + i)}{N^2 - \sum_{i=1}^{r}(x_i + x + i)} \quad (1)$$

Where,
r = Number of rows/columns in confusion matrix
xii = Number of observations in row i and column i
xi = Total number of rows i
x + i = Total number of columns i
N = Number of observations

Kappa value of > 0.79 are excellent; values between 0.6 and 0.79 are substantial; and values of 0.59 or less are moderate (Abdelkareem et al., 2018).

3.3.4 Areal changes of LULC classes

To estimate the changes between the various types of LULC to evaluate loss or gain in different classes in time periods, the study used the approach of percentage difference:

$$D = (Ab - Aa)/Aa \times 100\%, \quad (2)$$

Where, **D** refers to rate of change; **Aa** is the area in the initial year; and **Ab** is the area in the terminal year.

3.3.5 Determination of vegetation density in topographical zones

A combination of Normalized Difference Vegetation Index (NDVI) and ground truthing was used for vegetation density mapping. The use of NDVI was made because the area is in a water stressed region and vegetation type that changes significantly between the wet season and dry seasons. NDVI is good for vegetation cover density mapping even in water stress conditions when assessed along meteorological conditions as was considered in this study (Páscoa et al., 2020; Rousta et al., 2020; Zhang & Zhou, 2019). This NDVI test was used to compare vegetation location points to approximate environment change impact over the study time. Images of the same month was obtained for 2009 and 2021 and a close one by 2 months in 2001 and this was considered short time of major changes in vegetation.

A total of 100 location points were used for change comparisons for NDVI changes over the years.

$$NDVI = (NIR - Red) / (NIR + Red) \quad (3)$$

NIR - Near-Infrared

The values of NDVI range from -1 to 1. Dense vegetative land gives a high NDVI.

DEM topographic map (TM) points were used which represent the orthometric height. The geoid undulation of each point was calculated for subsequent transformation of ellipsoidal height to orthometric height (Moura-bueno et al., 2016). This is used for calculating the elevation errors (EE). The difference between the values of the reference elevation from the elevation value of each DEM was used to get differences field points (Moura-bueno et al., 2016; Odera & Fukuda, 2015). In the field, this was done by sampling of coordinate for depressions points and using them to check against DEM elevations (Xiao & Liu, 2012).

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Table 7: Distribution of elevation errors in vegetation mapping

	Difference in elevation (meters)				
Vegetation classes	MFS	0.3	0.2	0.3	0.1
	HDW	0.0	0.8	0.1	0.1
	MDW	0.2	0.0	0.2	0.4
	LDW	0.4	0.5	0.0	0.1
	WGL	0.00	0.2	0.0	0.1

3.4 Rainfall-runoff modelling

The SWAT model was used in this study and its modelling processes are shown in the chart below (Figure 9).

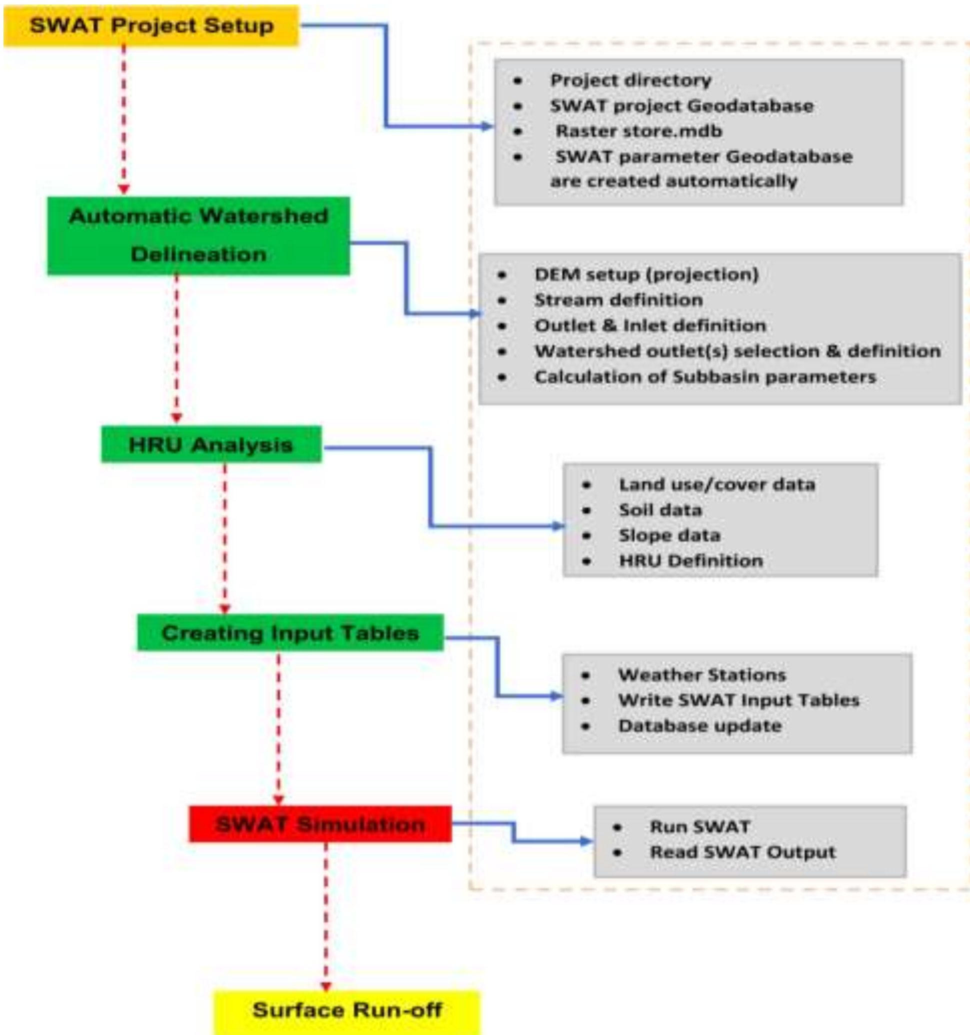


Figure 9: SWAT hydrological model process
(Source: Arnold et al., 2012)

3.4.1 Modelling approach

In this study, NASA-POWER meteorology satellite data was examined for applicability to model river flow using gauged rainfall data in SWAT model. The model requires inputs of minimum and maximum daily temperatures, daily precipitation, daily relative humidity, daily solar radiation and daily average wind speed data. The model was initially set up using daily downloaded from Global Weather Data for SWAT website (https://globalweather.tamu.edu/) [Accessed 30th May, 2019] for the years 2001 - 2019. The model was then applied to test applicability of NASA-POWER satellite data as an objective activity in this study.

Data utility testing process stated with statistical comparison of trends of NASA-POWER and SWAT WXGEN dataset for the catchment. In SWAT model, there is a WXGEN weather generator model which is used to generate acceptable climatic data for modelling purposes. Using the Green & Ampt infiltration method was used for simulation of rainfall runoff from the catchment. The WXGEN data was acquired for the period of 2001-2021.

Hydrological simulation of a river basin requires different type of data. The spatial data required by SWAT for hydrological simulation of a river basin are Digital Elevation Model (DEM), land use and land cover, soil map layer and weather. The WXGEN weather (assumption of consistency from 2001 to 2021) was comparatively used with NASA-POWER data to test trend in rainfall runoff simulation.

This was done to assess the trend similarity between both datasets served to accept use of NASA-POWER representing catchment hydrology trend before using it for modelling. The model representation of the catchment behaviour was then done by modelling river flow using measured rainfall and NASA-POWER data and calibration against gauged river flow. Modelling studies were done using soil data from the Food and Agriculture Organization of the United Nations (FAO) has been proven reliable; and was shown universal covering the basin expect for some variations top soil but this was considered acceptable given the area is hilly and partly rock surfaces.

3.4.2 Data sources and details

The digital elevation model was obtained from SRTM has projection system of WGS_1984_ UTM zone 37S with 30 meter spatial resolution was used. The sources of Geographical Information Systems (GIS), Remote Sensing (RS) and modelling software used in this research include;

i) The SWAT model was downloaded from the website (http://www.brc.tamus.edu/swat/soft_links.html). [Downloaded on 10th June, 2019].

ii) ArcGIS 10.5 was used to construct a SWAT model in ArcSWAT 10.5.24, the graphical user interface. This was obtained from

http://www.brc.tamus.edu/swat/ArcSWAT.html [Accessed 15th June, 2019].

iii) The model WXGEN daily WAS downloaded from Global Weather Data for SWAT website (https://globalweather.tamu.edu/) [Accessed 30th May, 2021).

iv) SWAT-CUP 2012 - used to automatically calibrate and validate results https://swat.tamu.edu/software/swat-cup [Accessed 4th May, 2019].

v) Soil data was also obtained from Land and Water Resource, FAO soil database at a scale of 1:5,000,000. Details on the soil map can be obtaineddvia http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases-FAOUNESCO-soil-mapoftheworld/en/ (accessed on 23 July 2020).

vi) NASA-POWER Data was downloaded from its Access Viewer (https://power.larc.nasa.gov/data-access-viewer/) [Accessed 20th August, 2021].

More information on data range, choices, characteristics and processes is given below;

(i) Land use and land cover data

Historical changes in land use and land cover, using satellite images at decadal scale over 20 year study period (2001, 2009, 2019) which is long time enough for change detection period for land use/cover mapping (Ridwan et al., 2018). The 2021 image was then used to check for changes during fieldwork time (2019-221). The best available Landsat satellite images were acquired for use in the above cases.

(ii) Soil data

The study used FAO nationally redefined soil database by IIAM developed in a research project on the status of soil resources in resources in Mozambique landscapes having scale of 1:2500, 000 (Mafalacusser, 2013). It was geo-processed to the dataset format compatible with Arc SWAT, appended to a user soil dataset, built a watershed specific soil lookup table, clipped and created a soil GIS layer for Incalaue catchment. The soil map provides the information about the soil type, soil classification and physical properties like texture, soil depth and soil drainage attributes needed for the SWAT model. Using the Arc SWAT soil database of US and soil properties such as clay content, sand content, loam content and hydrological group; a comparative study was made to identify SWAT user soils having the same characteristics as soils of the study area.

(iii) Weather/Meteorological data

Since there was no historical meteorological data, the study compared the applicability of NASA-POWER remotely sensed meteorological data and SWAT model data to reproduce rainfall runoff relationship in the area using field collected data. The NASA-POWER project provides daily data of near surface air temperature, relative humidity, rainfall, solar radiation and wind speed and direction. This study recognised that there are many available satellite meteorological datasets available, such as the Climate Forecast System Reanalysis (CFSR), the NASA Modern Era Retrospective-Analysis for Research and Applications (MERRA) and NASA Prediction of Worldwide Energy Resource (NASA POWER). There have not been many studies to evaluate use of the globally recognised NASA-POWER meteorological data in the region and specifically Northern Mozambique region.

The NASA POWER data has largely been used in agroclimatology modelling (Anaba et al., 2017; Asseng et al., 2017; Ceradini et al., 2021; Holthuijzen et al., 2021; Qi et al., 2019; Tadesse et al., 2015; Van Wart et al., 2015; Wu et al., 2021). The model was used for estimating the renewable energy potential in Africa (Sebastian & Hermann, Asami Miketa, 2014). The data has not been widely used in hydrological modelling on African continent

The NASA POWER project website allows users to easily access data which is available as a defined location by clipping it from regional and global coverage with daily averages. During data acquisition, the regional endpoint produces a time series dataset based on a bounding box of latitude and longitude coordinates defined by the user. The NASA-POWER website is user-friendly interface allows any end-user to easily have access to near-real time sound weather data (Rodrigues & Braga, 2021). The POWER project provides gridded database freely available global meteorology and surface solar energy climatology data. The data is available to download with a resolution of 1/2 by 1/2 arc degree longitude and latitude (resolution of 0.5°

latitude by 0.5° longitude). Data generation is funded through the NASA Earth Science Directorate Applied Science Program. The NASA provides solar and meteorological data sets from satellite systems that were set up under the NASA-POWER project.

3.4.3 Hydrologic landscape delineation and model set-up

(i) Catchment delineation

River catchment delineation was done using a Shuttle Radar Topographic Mission (STRM) Digital Elevation Model (DEM) Version 3.0 at a resolution of 1 arc second (30 m × 30 m) retrieved from the United States Geological Surveys (USGS) Earth Resources Observation and Science (EROS) archive via https://lta.cr.usgs.gov (accessed on 5 May 2019). The LULC information was obtained from remotely sensed 30m resolution images retrieved from USGS (section 3.3.1).

Hydrologic landscape was delineated following the steps outlined in the Arc-SWAT interface user's manual and SWAT model used for modelling rainfall runoff (Winchell et al., 2010). The Arc-SWAT is useful to delineate hydrologic boundaries to investigate hydrological processes during water resources management planning in river catchments (Osei et al., 2017; Pandey et al., 2021; Tudose et al., 2021). The watershed delineation process includes five major steps, DEM setup, stream definition, outlet and inlet definition, watershed outlets selection and definition and calculation of sub basin parameters. Automatic watershed delineation was done using a 30m x 30 DEM. First the DEM were projected into the same projection called UTM Zone 37S, which is projection parameter for the study area. Then, the DEM was clipped to a size slightly larger than the catchment before loading into the interface. A point of confluence of river Incalaue and river Lugenda was chosen as the outlet to delineate the complete Incalaue basin upstream area (Figure 10).

After the stage of DEM setup and the mask data was provided on the DEM, the model then automatically calculates the flow direction and flow accumulation. Consequently, stream networks, sub basin outlet, whole and sub watersheds were generated and topographic parameters calculated using the respective tools. The proven STRM DEM was used to avoid uncertainties associated with other products which have not been used for hydrologic applications in the region. Wide research has been done in NSR using STRM 90m x 90m DEM and the study used a resolution of 30m x 30m and avoided error budget uncertainties for other products such as LiDAR DEM (Wechsler, 2007)

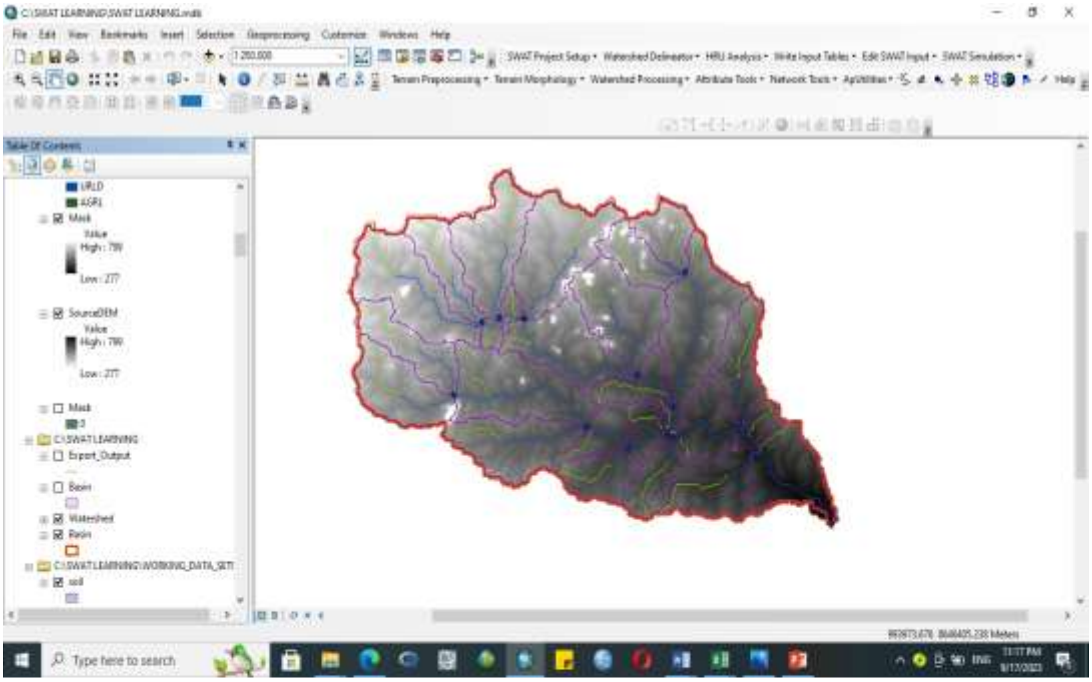


Figure 10: Automatic watershed delineation in SWAT model

(ii) Creating and determining Hydrologic Response Units (HRUs)

After watershed delineation, the creation of Hydrologic Response Units (HRUs) process was executed. Under the land use/soils/slope definition subsection, the geo-referenced classified land-use land-cover (secondary) raster map was imported into Arc SWAT in HRU Analysis section. The land use/cover, soil and slope data and their look up attribute tables were also imported and defined as required by SWAT. The LULC and soils were reclassified, overlapped and connected with the SWAT catalogues and ready for HRU definition. The LULC was reclassified into five classes in "SWAT Land Use Classification Table" namely; FRST – Forests, AGRL – Agricultural land, WATR – Water bodies, URBN – Settlements/Built-up, WETL – Wetlands and PAST – Pasture and Grasslands.

The soils were reclassified into three groups/types corresponding to SWAT database for FAO soils in "SWAT Soil Classification Table". These included BENSON = Black loamy over red clay loams, SWANTON = Dark red clays sometimes underlain by laterite and WEIDER = Grey-humose clays, Grey sands and Red sandy-clay- loamy soils.

Also, in SWAT Slope Classification Table, five slope classes were set each having the lower and upper class limit in percentage (%) namely; class 1 (0 – 5%), class 2 (5 – 20%), class 3 (20 – 30%), class 4 (30 – 55%) and class 5 (55 – 99%). When the overlay option was executed, the HRU feature class and Overlay reports were created. In HRU definition, the threshold levels set for land use, soil and slope were used to define the number of HRUs within the sub-basin as well as the watershed. The minimum threshold areas of 6% for land use, 4% for soil class and 2% for slope were set. During this process, SWAT divides the basins into smaller divisions which have the particular soil, land use/cover and slope range combination known as HRU. The option to create multiple HRUs per sub-catchment was enabled and generalized based on dominant land use, soil, and slope characteristics was selected.

For one HRU, SWAT uses the dominant land uses and soil types to designate a single HRU for each sub-basin. To have multiple HRUs in a sub-catchment, the user needs to identify a threshold percentage value of LULC and soil type for each HRU. The number of HRUs is defined by eliminating the percent land use, soil, and slope values that cover a of the sub-catchment area less than the threshold level (Figure 11). Finally, the report was created with land use, soil classification, and slope characteristics for the whole Incalaue catchment, including 241 HRU’s and 20 sub-watersheds (Dominant HRUs).

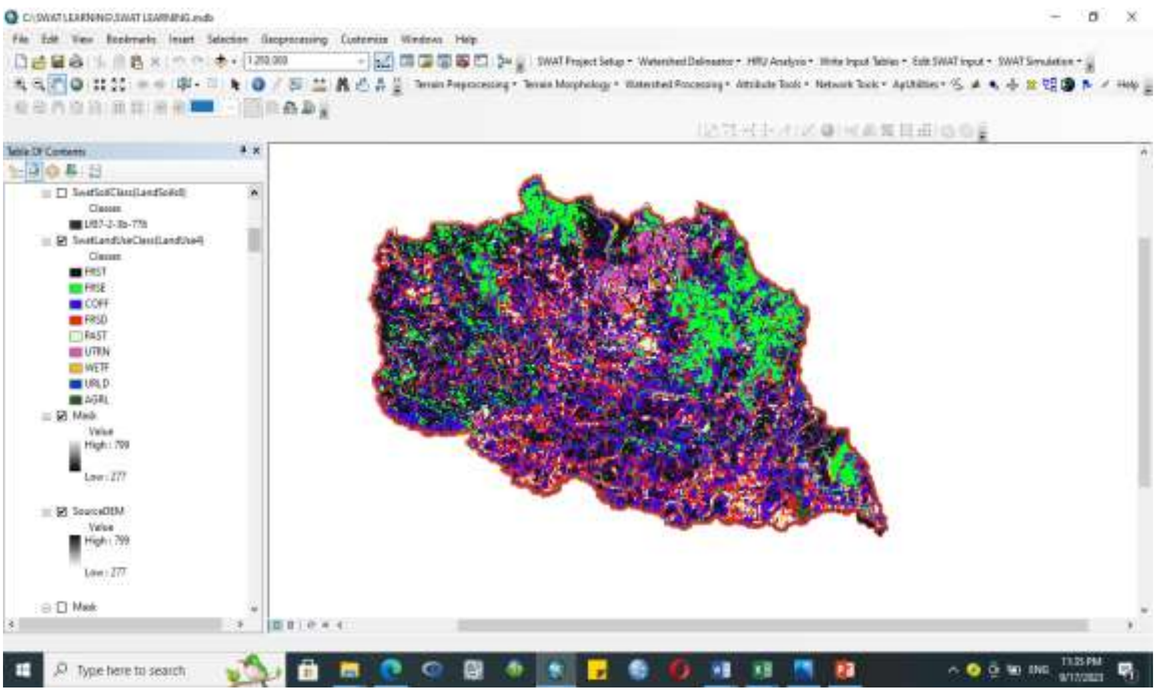


Figure 11: Definition of the HRUs

(iii) **Weather data definition**

The WXGEN_user option of generating weather data was used. Only the files containing the coordinate locations of the weather data (precipitation (pcp), temperature (tmp), relative humidity (rh), wind speed (wind) and solar radiation (solar) were imported into SWAT. All swat input tables were selected and written automatically. The SWAT model was finally setup for simulation by selecting and defining the simulation period of 2001 to 2021, rainfall-runoff/routing method, rainfall distribution and potential evapotranspiration method in the "SWAT Setup and Run" screen. The first 3 years were used as a warm-up period to allow the processes simulated to reach a dynamic equilibrium and decrease the uncertainty of the initial conditions of the model.

3.4.4 Model calibration and validation

The auto-calibration tool, SWAT-CUP with the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm was used for model calibration. The SUFI-2 estimates both parameter and model uncertainties in hydrological models. It is capable of analysing a large number of parameters and measured simultaneously. It also requires the smallest number of model runs to achieve a good calibration and uncertainty results and can be easily linked to SWAT- CUP. SWAT model was calibrated for monthly river flow (2001 – 2009) and validated using field gauged data (2009-2021). The model performance was tested by comparison with the observed stream flows that were collected during the study.

Parameter uncertainty in SUFI-2 accounts for sources of uncertainties in the model. Sources of error can be rainfall data, conceptual model, parameters and measured data that is used. To evaluate the strength of calibration in addition to Coefficient of Correlation (R^2) and Nash–Sutcliff Efficiency (NSE), the Mean Root Square Error (MRSE) test was used. NSE is a normalized statistic that determines the relative magnitude of the residual variance compared to the measured data variance. The desired 1:1 line fit between observed and simulated data and is computed as:

$$NSE = 1 - \left[\frac{\sum_i^n (Q_{obs_i} - Q_{sim_i})^2}{\sum_i^n (Q_{obs_i} - Q_{mean})^2} \right] \quad (4)$$

Where, n is the total number of observations, Qsimi and Qobsi are the simulated and observed discharges at the Observation, respectively, and Qmean is the mean of observed data over the modelling time.

3.4.5 Modelling partial contribution of LULC and climate to rainfall-runoff

Climate variability and land-use change are factors that can differently alter hydrology of a river catchment, having effects on river flow separately or combined cumulatively as process (Figure 12). Research has shown that land use and climate change separately have effects on hydrological processes; and that each should not be quantified separately because the total contribution of each factor does not make 100% (Iqbal et al., 2022). The disadvantage of the conventional separate effects approach is that, the other factors' effects are not considered; and therefore it requires further differentiation of the combined effect to assess strength for the study period considered (Yang et al., 2017).

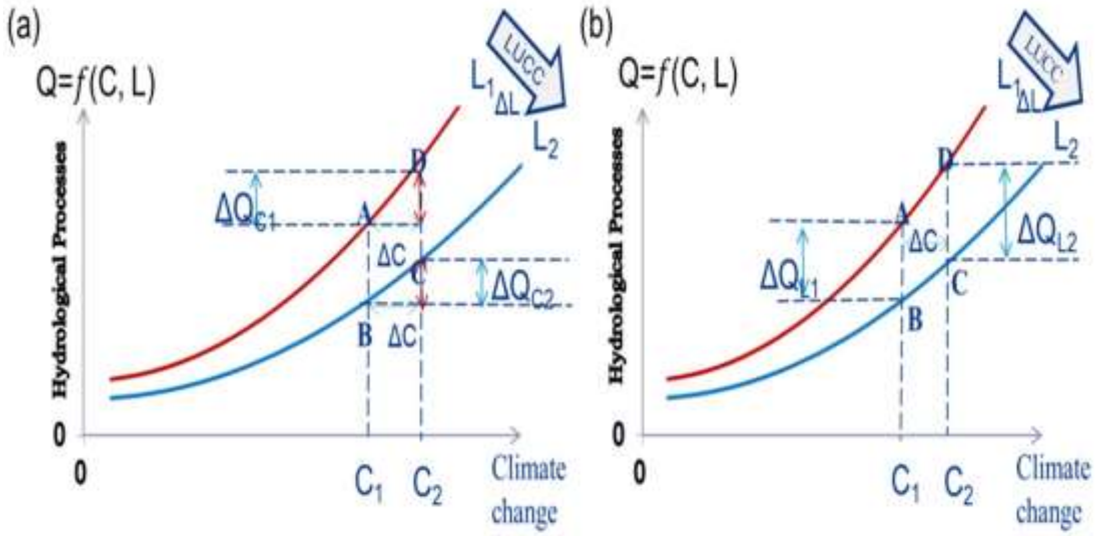


Figure 12: Approach used to assess climate (a) and LULCC (b) on river flow

The approach used involved analysis of variations in river flow yield under land use and climate conditions for selected time steps using SWAT model. Land use; and land cover conditions were defined for both periods by two land use and land cover maps, L1 (2009) and L2 (2021) and similarly climate data as C1 and C2 respectively. The land use and climate configurations (C1, C2, L1, and L2) were used to compute the integrated modelling scenarios (SI, S2, S3, and S4). These models were of fixed land use for 2001-2009 (S1); fixed land use for 2010-2021 (S2); fixed climate for 2001-2009 (S3); fixed climate for 2010-2021 (S4).

Monthly data was used for partial simulations in SWAT models for the years 2001 up to 2021. The study used 2 land use and land cover maps with year 2009 (which represented 2001 – 2009) as the first calibration phase assessment; and 2021 (which represented 2010 – 2021). NASA-POWER Hydro-meteorological data used (2001–2021) was divided into the calibration periods (2001–2009) and (2010–2021). Hydro-meteorological data includes precipitation, temperature (maximum and minimum), humidity, sunshine duration, evapotranspiration and wind speed.

$$\Delta Q_L = \frac{1}{2}\left[(Q_{C1}^{L2} - Q_{C1}^{L1}) + (Q_{C2}^{L2} - Q_{C2}^{L1})\right] \tag{5}$$

$$\Delta Q = Q_{C2}^{L2} - Q_{C1}^{L1} \tag{6}$$

$$\Delta Q_C = \frac{1}{2}\left[(Q_{C2}^{L1} - Q_{C1}^{L1}) + (Q_{C2}^{L2} - Q_{C1}^{L2})\right] \tag{7}$$

Where; L = Land use/cover; C = Climate; and Q = River flow

The method assumes that change in rainfall runoff reflect change in climate and land use and land/cover variability. These changes can overall come from intra-annual climatic effects such as changes precipitation intensity and amounts; and changes can come from crop cover as potential evapotranspiration (Mwangi et al., 2014; Roderick & Farquhar, 2011).

In this analysis, NASA-POWER simulated results were adopted instead of the observed data (ungauged river catchment) to compare the hydrological effects of land use and climate change of the years for the adopted scenarios. This was because the catchment did not have historical climatic data and NASA-POWER data had been shown reliable for modelling trends.

3.5 Rainfall-runoff linear regression analysis

Regression analysis was used to model the relationship rainfall and river flow as variables in gauged data. Rainfall was considered an independent variable/predictor (***β***) and river flow (Y) as a response in the catchment. Below is the linear regression formula that was used (Equation 7)

$$\boldsymbol{E\ (Y) = \beta_0 + \beta_1\chi} \tag{7}$$

Where = β_0 = intercept and β_1 = slope of the regression coefficients followed by χ as independent variable and Y as dependent variable.

The slope β_1 can be interpreted as the change in the mean value of Y for a unit change in χ. The random error term, ϵ, is assumed to follow the normal distribution with a mean of 0 and variance of σ^2. Since Y is the sum of this random term and the mean value, E (Y), which is a constant, the variance of Y at any given value of χ is also σ^2. Therefore, at any given value of χ, say χ_i, the dependent variable Y follows a normal distribution with a mean of $\beta_0 + \beta_1$ and a standard deviation of σ. The main purpose of this test was to derive the relationship of rainfall and runoff as indicated by river discharge.

Before performing the linear regression analysis a check for the following data quality issues was performed. Specifically, I checked for missing values visually; outliers using the linear regression in Microsoft Excel; and performed several tests including multicollinearity, heteroscedasticity and normality of the data. Multicollinearity test was performed to avoid Type II Errors. This study used the Variance Inflation Factor (VIF) and *tolerance* to determine whether the independent variables are highly correlated and the variance of the coefficient are inflated. The relevant statistics is as follows:

$$\text{VIF} = \frac{1}{1-R^2} = \frac{1}{Tolerance}$$

where R^2 is the unadjusted coefficient of determination for regressing the ith independent variable on the remaining ones. The results of this test showed that the presence of multicollinearity was absent in the regression model.

The test for Homoscedasticity was verified by taking the difference between predicted and observed values, i.e., the residuals/ error term and the degree of variance over different data points should be the same. The Breusch-Pagan test was used to determine whether or not heteroscedasticity is present in a regression model.

The hypothesis tested was: $H0: Var (\varepsilon i \mid xi) = \sigma 2$

This means, homoscedasticity is present (the residuals are distributed with equal variance)

$$H1: Var (\varepsilon i \mid xi) = \sigma 2i$$

This means that heteroscedasticity is present (the residuals are not distributed with equal variance)

The following steps was used to perform the Breusch-Pagan test:

- Fit the Multiple regression model.
- Calculate the squared residuals of the model.
- Fit a new regression model, using the squared residuals as the response values.
- Calculate the Chi-Square test statistic and it is calculated as:

$$LM = n *R^2 \sim X2(K)$$

where n is the total number of observations, k is the degree of freedom, and R^2 is the R-squared of the new regression model that used the squared residuals as the response values. For this study, the test result shows that homoscedasticity is present and the residuals are distributed with equal variance. An assessment of the normality of data is a prerequisite for many statistical tests because normal data is an underlying assumption in parametric testing (Boakye & Agbedra, 2016; Mishra et al., 2019). One of the most common requirements for hypothesis testing is that the data used must be normally distributed. For this study, the Shapiro–Wilk test methods was used to test the normality of the data.

The hypothesis tested was:

H0: the frequency distribution of the data fit the normally distribution. i.e. U~N (μ, σ2)

The result from the normality test shows that there is a symmetrical plot of data around its mean value indicating that the date follows a normal distribution.

3.6 Limitations of the study and uncertainties

The study was limited by COVID-19 pandemic with the area being at a high risk due to proximity to Tanzania which was a hotspot area as SOPs where largely not used with high death rates. This limited travel to the field because at some point there were restrictions for travel around Niassa Reserve and monitoring of field assistants was not possible.

CHAPTER FOUR

RESULTS

4.1 Objective 1: Assessment of LULC and river flow partial contribution areas

This section presents results of the analysis but discussion of this data can be found in the next chapter or complete details found in the published papers in Appendices. The paper was:

i. *Assessing Land Use/Cover Basing on Connectivity, Changes and Drivers over 20 Years to Recommend Conservation in Incalaue River Basin, Niassa Special Reserve in Mozambique.* Journal of Environmental Science and Engineering **A11** (2022) 13-34 doi:10.17265/2162-5298/2022.01.003

ii. *Assessment of conservation status of riparian vascular plant species in a dry season exposed flood plain area of Incalaue river catchment, Niassa Special Reserve, Northern Mozambique.* *Environ. Res.: Ecology* **3** 015001. DOI 10.1088/2752-664X/ad0e7a

4.1.1 Dominant LULC classes in sub-catchments

There were 11 sub-catchments and 6 vegetation classes of Mountain Forest (MFS), High Density Woodland (HDW), Medium Density Woodland (MDW), Low Density Woodland (LDW), Wooded Grasslands (WGL) and Wetland (WET) (Figure 13 and Table 8). The rest of the catchment was under built up area, burned areas and inselbergs (ISL), recently burned area (RBA) and Built-up areas (BUL).

The study found that vegetation does not necessarily follow topographic and river flow patterns with wetlands existing upstream (around 799 m. asl) and downstream (around 277 m. asl). Inselbergs are well distributed across the catchment and it seems there were areas of dry vegetation sections that were all mapped as recently burned areas also across all sub-catchments.

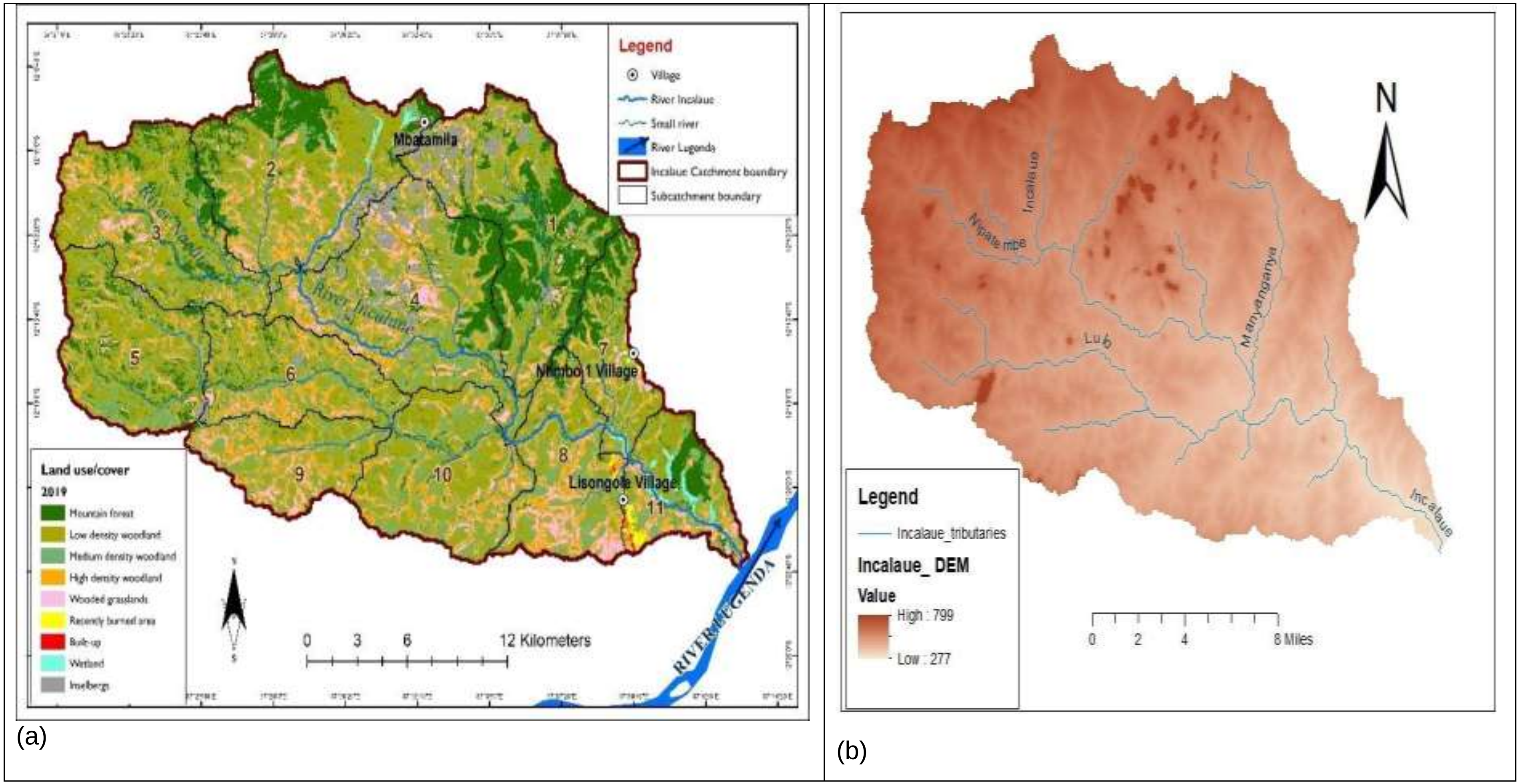


Figure 13: Lad us and land /cover (a) and elevation (b) maps of Incalaue catchment

Table 8: Areal LULC cover in sub-catchments (Sk. km)

Sub-catchment	Built-up	Medium density woodland	High density woodland	Wooded grasslands	Inselbergs	Recently burned area	Mountain forest	Wetland	Low-density woodland	Grand Total
1		10.15	5.95	17.52	19.82	30.60			3.43	87.46
2	0.12	15.84	2.82	28.66	22.09	21.39		0.99	5.59	97.51
3		12.10	0.06	29.83	17.30	11.78			3.61	74.68
4		20.98	6.86	20.74	28.44	13.11			9.70	99.83
5		8.10	0.55	26.29	15.95	8.33			1.49	60.71
6		12.72	0.58	16.19	15.48	3.41			2.49	50.86
7	0.04	5.61	0.00	9.09	8.81	7.52	0.50	0.42	1.96	33.95
8	0.07	14.66	0.17	11.34	16.57	2.25	0.30	0.03	6.68	52.07
9		12.17		10.42	12.89	1.06			3.44	39.98
10		14.54		21.80	22.33	1.83			3.10	63.60
11	0.24	6.29		8.24	10.41	5.65	1.24	1.69	2.59	36.36
Grand Total	0.47	133.16	17.00	200.12	190.09	106.93	2.03	3.14	44.08	697.02

4.1.2 Satellite image classification accuracy

Landsat-8 OLI Satellite images for the year using the 2021 that was classified above gave an accuracy of 87.51% for sampled field point locations using the vegetation classification that was adopted for the study (Ribeiro et al., 2008b) . The accuracy of accuracy test for previous years were 85% (2001) and 87% (2009) and this was attributed to natural land cover change and satellite image timing differences.

In this process of classification image assessment for the 2021 image, a total of 400 points were randomly selected on the image of 2021 for classification and only 287 were accessible out of which 246 were properly classified (Table 9).

Table 9: Confusion matrix

	HDW	MWL	LDW	WGL	MFS	RBA	ISL	Total	Correctly sampled
HDW	34	2	0	0	2	0	0	38	34
MDW	1	23	2	0	1	0	0	27	23
LDW	1	4	31	6	2	0	0	44	31
WG	0	1	6	72	0	0	0	79	72
MF	0	0	0	0	26	0	0	26	26
RBA	0	0	0	0	0	29	3	32	29
ISL	0	0	0	0	0	10	31	41	31
Total	36	30	39	78	31	39	34	287	246

The overall classification accuracy = percentage ratio of number of correctly sampled point locations.

Accuracy = (246/287) *100 = 85.71%.

4.1.3 Vegetation cover variations in topographic zones

Topography ranges from 360 m a.s.l to 580 m. a.s.l with the largest vegetation-class dominance being MDW (27.29%) in the elevation band 410 m a.s.l to 430 m a.s.l (Figure 11. The landscape area has high elevation section of the steep gradient which can contribute to erosion deposition in lowland areas and contributes to vegetation classes there which can explain the wide distribution of classes across the landscape. MFS is easily accessible from Mbatamila and Ntimbo 1 and grow at < 580 m.a.s.l. Vegetation largely characterized by woodlands in the area below this elevation. HDWs are most common in sub-catchment 3 where interestingly there is no small-scale agriculture which is possibly an indicator of vegetation succession section dominance.

Wetlands are common in sub-catchment 11 downstream of the catchment which is hydrologically expected for a flood plain. There is more MDW in sub-catchment 10 and this is the sub-catchment with evenly distributed vegetation cover. Vegetation types do not necessarily follow landform as observed in classification with upstream (440-510 m a.s.l) having MFS which also existed in lower altitude areas (370-430 m a.s.l). Apart from WET, all the other land-cover classes exist in the midstream section. Except for RBA and built up, the upstream section had the same classes as downstream.

4.1.4 Comparison of LULC in studied years

Land use/cover change analysis was done for years 2001, 2009 and 2021 covered by this study showed that there was progressive increase of area covered by taller vegetation for the study period in the order of MDW> HDW >MFS (Table 10 & 11).

Table 10: Areal LULCC in studied years (Sq. km)

No.	LULC	2001		2009		2021	
		Area	%	Area	%	Area	%
1	MFS	68.54	9.83	87.13	12.50	105.95	15.20
2	LDW	154.62	22.18	173.07	24.83	43.54	6.25
3	MDW	88.17	12.65	114.52	16.43	133.2	19.11
4	HDW	161.24	23.13	196.02	28.12	190.19	27.29
5	WGL	210.49	30.20	103.99	14.92	200.49	28.76
6	RBA	2.11	0.30	2.88	0.41	3.03	0.43
7	BULT	0.24	0.03	0.37	0.05	0.48	0.07
8	WET	3.56	0.51	3.49	0.50	3.14	0.45
9	ISL	8.05	1.15	15.55	2.23	17	2.44
	Total	697.02		697.02		697.02	

There were losses for WET for vegetation and gains for ISL and built-up environment (Table 11).

Table 11: Percentage LULCC

No.	LULC	2001 to 2009	2009 to 2021	2001 to 2021
1	MFS	2.67	2.70	5.37
2	LDW	2.65	-18.58	-15.94
3	MDW	3.78	2.68	6.46
4	HDW	4.99	-0.84	4.16
5	WGL	-15.28	13.84	-1.44
6	RBA	0.11	0.02	0.13
7	BULT	0.02	0.02	0.04
8	WET	+0.01	0.05	-0.06
9	ISL	1.08	0.21	1.28

A comparative land use and land cover transition matrix was done for the study time (2001 – 2021) to assess specific changes within specific changes for vegetation classes (Table 12).

Table 12: Land use and land cover change transition matrix

	MFS	MDW	HDW	WGL	LDW	WET	RBA	ISL	BUL	Total
MFS	26.87	27.22	20.14	5.87	25.99	0.32	0	0.52	0.02	106.95
MDW	17.97	14.4	26.45	24.36	47.66	1.48	0	0.86	0.02	133.2
HDW	18.33	27.8	91.75	18.61	31.7	0.4	0.18	1.37	0.05	190.19
WGL	7.68	8.48	7.78	135.01	40.34	0.28	0.31	0.61	0	200.49
LDW	2.57	5.65	12.12	15.38	5.3	0.69	0.28	1.53	0.02	43.54
WET	0.54	0.68	0.61	0.16	0.76	0.39	0	0	0	3.14
RBA	0.04	0.26	0.4	0	0.04	0	1.18	0	0.11	2.03
ISL	4.48	3.63	1.91	1.06	2.76	0	0	3.16	0	17
BUL	0.06	0.05	0.08	0.04	0.07	0	0.16	0	0.02	0.48
Total	78.54	88.17	161.24	200.49	154.62	3.56	2.11	8.05	0.24	697.02

The increase in the area covered by ISL was possibly from soil erosion opening up rock and area loss of RBA which reduces for 2021. This can also result from opened up area because the area has vegetation that shades their leaves burning. Overall, there is a larger share of vegetation compared to other land use and land cover classes (Figure 14).

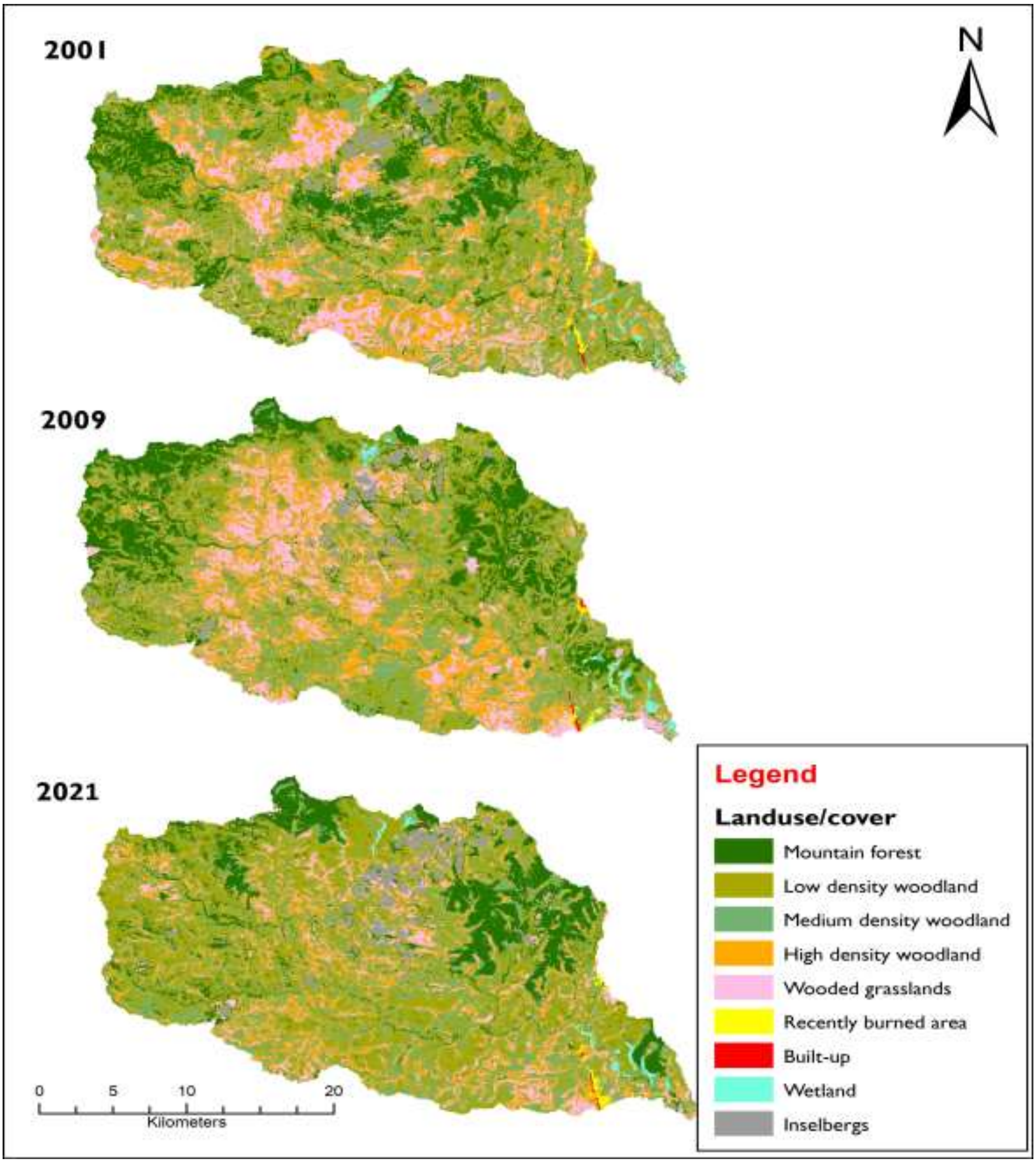


Figure 14: Land use and land cover change in Incalaue catchment

4.1.5 Vegetation species in landscape drainage hydrologic zones

The wet season had more species in the selected GCPs plots (Figure 6) in the wet season than in the dry season. The upstream areas largely dominated by MFS zone had taller vegetation species compared to only woodland areas (Table 13).

Table 13: Vegetation species in dense tall upstream area

1	*Julbernardia globlifera* (Benth.) Troupin
2	*Blepharis panduriformis* Lindau
3	*Brachystegia boehmii* Taub.
4	*Sterculia steno* H. J. P Winkl
5	*Millettia stuhlmannii* Taub
6	*Pteleopsis myrtifolia* (M. A. Lawson) Gere & Boatwr
7	*Brachystegia spiciformis* Benth
8	*Terminalia sericea* Burch ex DC
9	*Adansonia digitata* L.

All upstream tree species above were also found in some midstream plots and those near riverine and valley areas (Table 14). These environments have additional species in an environment which is visibly denser in the wet season.

Table 14: Taller vegetation species mainly in midstream and lowland areas

1	*Pseudolachnostylis maprouneifolia* Pax
2	*Pterocarpus angolensis* DC
3	*Burkea Africana* Hook.sa
4	*Acacia goetzei* Harms
5	*Casuarina junghuhniana* Miq.
6	*Cissampelos pareira* L. var. *hirsute* (Burch. ex DC.)
7	*Combretum kraussii*Hochst.
8	*Combretum mossambicense*(Klotzsch) Engl.
9	*Croton gossweileri* Hutc*h.*
10	*Cyphostemma spinosopilosum* (Gilg & M. Brandt) *Desc.*
11	*Dichrostachys cinerea* subsp. *africana var* (L.) Wight & Arn.
12	*Flacourtia indica* (Burm. f.) Merr.

13	*Jacaranda mimosifolia* D. Don
14	*Julbernardia globiflora* (Benth.) Troupin
15	*Landolphia kirkii* Dyer ex Hook. f.
16	*Pterocarpus lucens Lepr. exGuill. & Perr.* subsp. *Antunesii* (Taub.) Rojo
17	*Strychnos spinosa* Lam.
18	*Syzygium guineense* (Willd.) DC.
19	*Vachellia davyi* (N.E.Br.) Kyal. & Boatwr.
20	*Tribulus cistoides* L.
21	*Vangueria infausta* Burch. subsp. *infausta*

Grass and shrub-species were found mainly in plots mainly in lowland and near riverine environments (Table 15). These were mainly located in loam-sand soil dominating valley areas in the sections away from the river mainly in soil trapped between rocks.

Table 15: Grass and shrub vegetation species

1	*Trichocladum panicum.* Hack. ex K. Schum
2	*Hyparrhenia variabilis* Stapf
3	*Xerophyta spekei* Baker
4	*Sansevieria ehrenbergii* Schweinf. ex Baker
5	*Dewildemaniana pycnostachys* Robyns & Lebrun, Rev
6	*Themeda triandra* Forssk.
7	*Hyparrhenia newtonii* (Hack.) Stapf var. macra Stapf.
8	*Aristida adscensionis* L.

4.1.6 Normalized Difference Vegetation Index (NDVI)

Comparison of statistics from images used for the different years was used to examine trends in vegetation cover wetness/density and showed sections of vegetation got denser for others after from 2001 for the satellite images used. The NDVI maps show 2019 with wetter vegetation than 2001; and both more than 2009 (Table 16).

Table 16: NDVI statistics from images used

	Lowest	Highest	Mean	Standard deviation
2001	0.075797	0.294118	0.170697	0.070305
2009	0.040816	0.370787	0.235522	0.079987
2019	0.141511	0.325352	0.255082	0.040070

The NDVI maps equally showed 2019 with wetter vegetation than 2001; and both more than 2009 (Figure 15). This may be attributed to the high coverage of shade vegetation in 2019 that support undergrowth vegetation.

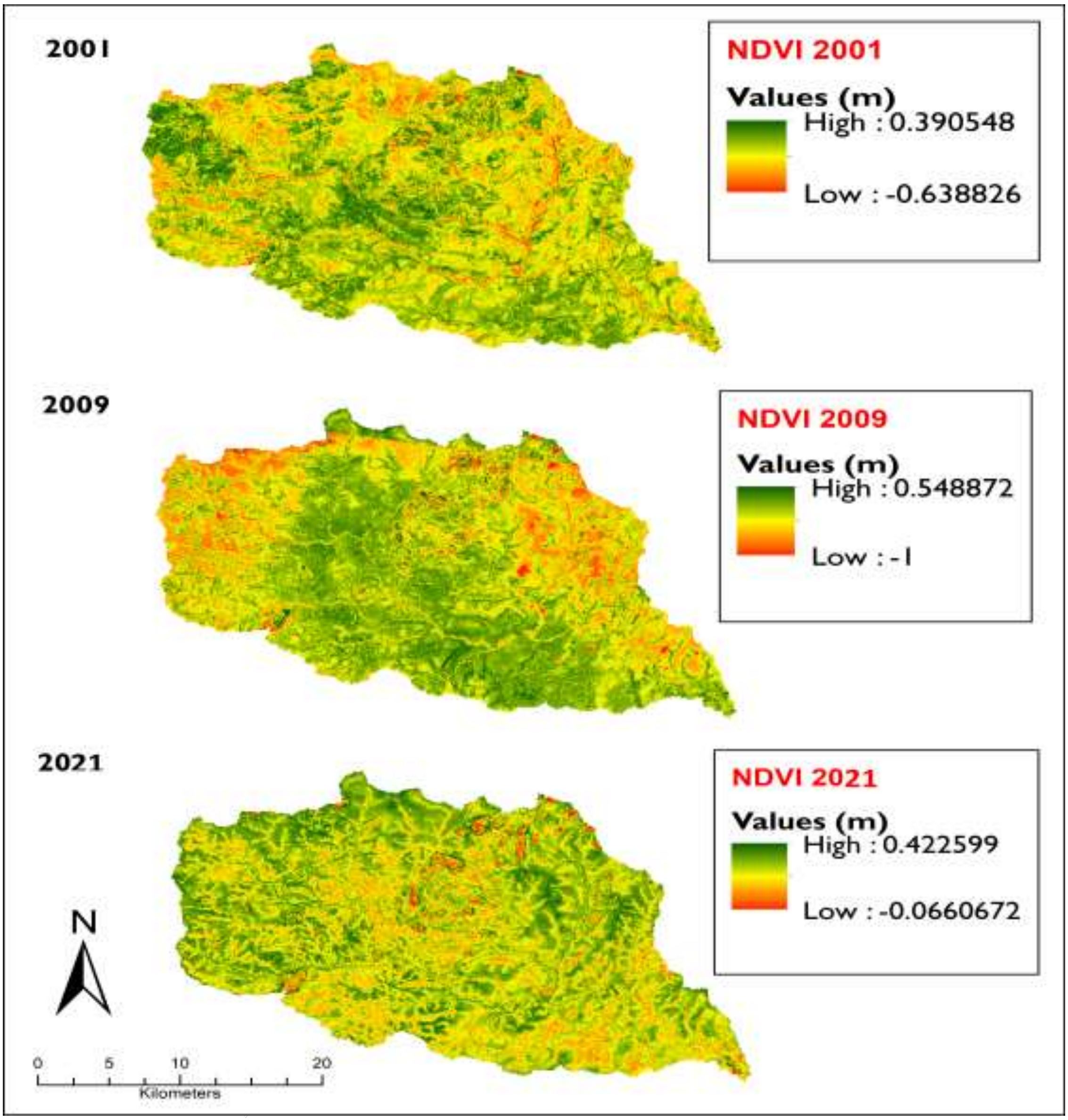


Figure 15: NDVI change for selected images in studied time period

4.1.7 Conservation of seasonally important riparian vegetation species

This study assessed composition and conservation status of riparian species in an exposed river basin downstream location. The river catchment has a harsh seasonal effect on vegetation where vegetation largely sheds leaves apart from the riparian vegetation which then become important for people and wildlife.

The sampled riparian vegetated river section was therefore divided into three segments (S1, S2 and S3) in the downstream direction. Vegetation was found growing in almost sandy soil deposit segments of around 60 m so this was chosen as sampling segment length along the river in the layout design of the sampling segments. Plants of height >25 cm in each of the selected unit plots were identified, classified, counted and recorded. Purposive sampling was used in selection of sites and respondents to maximise data collection. The study found 19 species belonging to 15 families with 52.63% of them having frequency of ≥50% in sampling plots (Table 17). There were 10 species that that are endemic to the sub-Sharan Africa Region. Fabaceae was the dominant family with 5 species. The species with the highest population was *Flacourtia indica* (Burm. f.) Merr. Species richness ranged from 0.35 to 0.98 with a mean of 0.66±0.22. IVI ranged from 34.70 (*Flacourtia indica* (Burm. f.) Merr) to 4.43 (*Tribulus cistoides* L.) with a mean of 15.79±7.79. Threats of species loss and ecosystem disturbance were agriculture, infrastructure development and plant harvests. There was a reported decline in species availability over the previous 10 years by 18.7% of respondents. Results added to the existing studies and records of vegetation species of conservation value that area exposed to loss in NSR. This study advances research on vegetation range dynamics in NSR and presents a need to mitigate human land use impacts on riparian vegetation species composition. A big percentage (52.63%) of species had more individuals in the river channel than on the riparian bank; and with exception of *Tribulus cistoides* L., all species were available both in the river channel area and on the bank sides.

Table 17: Species list

	Species name	Family	Genus
1	*Senegalia goetzei* (Harms) Kyal. & Boatwr. subsp *goetzei*	Fabaceae	*Senegalia* Raf.
2	*Brachystegia boehmii* Taub	Fabaceae	*Brachystegia* Benth
3	*Casuarina junghuhniana* Miq.	Casuarinaceae	*Casuarina* L.
4	*Cissampelos pareira* L. var. *hirsuta* (Burch. ex DC.) Forman	Menispermaceae	*Cissampelos* L.
5	*Combretum kraussii* Hochst.	Combretaceae	*Combretum* Loefl
6	*Combretum mossambicense* (Klotzsch) Engl.	Combretaceae	*Combretum* Loefl
7	*Croton gossweileri* Hutch.	Euphorbiaceae	*Croton* L.
8	*Cyphostemma spinosopilosum* (Gilg & M.Brandt) Desc.	Vitaceae	*Cyphostemma* (Planch.)
9	*Dichrostachys cinerea* (L.) Wight & Arn. subsp. *africana* Brenan & Brummitt	Fabaceae	*Dichrostachys* (A.DC) Wight & Arn.
10	*Flacourtia indica* (Burm. f.) Merr.	Salicaceae	*Flacourtia* Comm. ex L'Hér
11	*Jacaranda mimosifolia* D.Don	Bignoniaceae	*Jacaranda* Juss
12	*Julbernardia globiflora* (Benth.) Troupin	Fabaceae	*Julbernardia* Pellegr.
13	*Landolphia kirkii* Dyer ex Hook. f.	Apocynaceae	*Landolphia* P.Beauv
14	*Pterocarpus lucens* Lepr. ex Guill. & Perr. subsp. *antunesii* (Taub.) Rojo	Fabaceae	*Pterocarpus* Jacq
15	*Strychnos spinosa* Lam.	Loganiaceae	*Strychnos* L.
16	*Syzygium guineense* (Willd.) DC. subsp. guineense	Myrtaceae	*Syzygium* Gaertn
17	*Vachellia davyi* (N.E.Br.) Kyal. & Boatwr.	Fabaceae	*Vachellia* Wight & Arn.
18	*Tribulus cistoides* L.	Zygophyllaceae	*Tribulus* L.
19	*Tapiphyllum velutinum* Robyns	Rubiaceae	*Velutinum* Juss

The human activities that could result in species loss and ecosystem disturbance that were recorded.

i. Cutting of trees to make shade in the gardens in preparation for wet season, removing vegetation to create routes for water access, gardens on river edges, river crossing informal bridges (observed at S1, S2 and S3; and also reported by the community).

ii. Plant harvest for domestic and medicinal purposes (reported by the community),

iii. Uprooted dead plants and clearing of riparian vegetation in preparation of bankside agriculture (S1, S2 and S3); and

iv. Walk throughs across the river were observed to be resulting in cut stems and plucking on leaves (observed in S1); and uprooting of plants on pathways leading to water pools that remain in the river meander rock enclaves (S1 and S3).

All household heads reported that families pick and use parts of green plants of riparian species. There were 47.96% of household heads/representatives that expressed uncertainty over changes in riparian area species; 18.7% reported decrease; 5.7% reported no change; and 27.64% reported increase. The harvested parts of the plants were reported by respondent as leaves (43.82%), stems (29.21%) and fruits (26.97%).

IVI ranged from 34.70 (*Flacourtia indica* (Burm. f.) Merr) to 4.43 (*Tribulus cistoides* L.). The IVI had a mean of 15.79±7.79 among the species. High standard deviation means data are not clustered around the mean which shows species have a wider range in number of plants sampled. Relative density ranged from 15.53 (*Flacourtia indica* (Burm. f.) Merr) to 0.49 (*Tribulus cistoides* L).

The number of plants in a single sampling plot ranged from 6 to 54 with average of 17.7. This showed that plants were well distributed in the plots. Species richness ranged from 0.3484 to 1.0451 with mean of 0.6561±0.2118. Species are averagely well balanced in occurrence in the riparian zone with about half of them above mean IVI (Table 18). There were more plant species present in the area below the bridge which crossed the studied downstream river catchment section with human land use in the dry season when upstream area dries-up (Figure 16). The sampling segments S1 and S2 where before the road crossing while S3 was after the bridge crossing.

Table 18: Species frequencies

Species	Total number	RD (%)	RF (%)	RA (%)	IVI
Senegalia goetzei (Harms) Kyal. & Boatwr. subsp *goetzei*	5	2.43	3.70	3.78	9.91
Brachystegia boehmii Taub	13	6.31	5.56	6.54	18.41
Casuarina junghuhniana Miq.	9	4.37	4.63	5.44	14.44
Cissampelos pareira L. var. *hirsuta* (Burch. ex DC.)	18	8.74	7.41	6.80	22.94
Combretum kraussii Hochst.	5	2.43	3.70	3.78	9.91
Combretum mossambicense (Klotzsch) Engl.	11	5.34	5.56	5.54	16.43
Croton gossweileri Hutch.	7	3.40		3.52	12.48
Cyphostemma spinosopilosum (Gilg & M.Brandt) Desc.	5	2.43	4.63	4.23	11.29
Dichrostachys cinerea (L.) Wight & Arn. subsp. *africana* Brenan & Brummit	23	11.17	6.48	9.93	27.57
Flacourtia indica (Burm. f.) Merr.	32	15.53	11.11	8.06	34.70
Jacaranda mimosifolia D.Don	4	1.94	3.70	3.02	8.67
Julbernardia globiflora (Benth.)	8	3.88	6.48	3.45	13.82
Landolphia kirkii Dyer ex Hook. f.	20	9.71	7.41	7.55	24.67
Pterocarpus lucens Lepr. ex Guill. & Perr. subsp. *antunesii* (Taub.) Rojo	5	2.43	3.70	3.78	9.91
Strychnos spinosa Lam.	3	1.46	2.78	3.02	7.25
Syzygium guineense (Willd.) DC.	16	7.77	7.41	6.04	21.22
Vachellia davyi (N.E.Br.) Kyal. & Boatwr.	15	7.28	6.48	6.47	20.24
Tribulus cistoides L.	1	0.49	0.93	3.02	4.43
Tapiphyllum velutinum Robyns	6	2.91	2.78	6.04	11.73

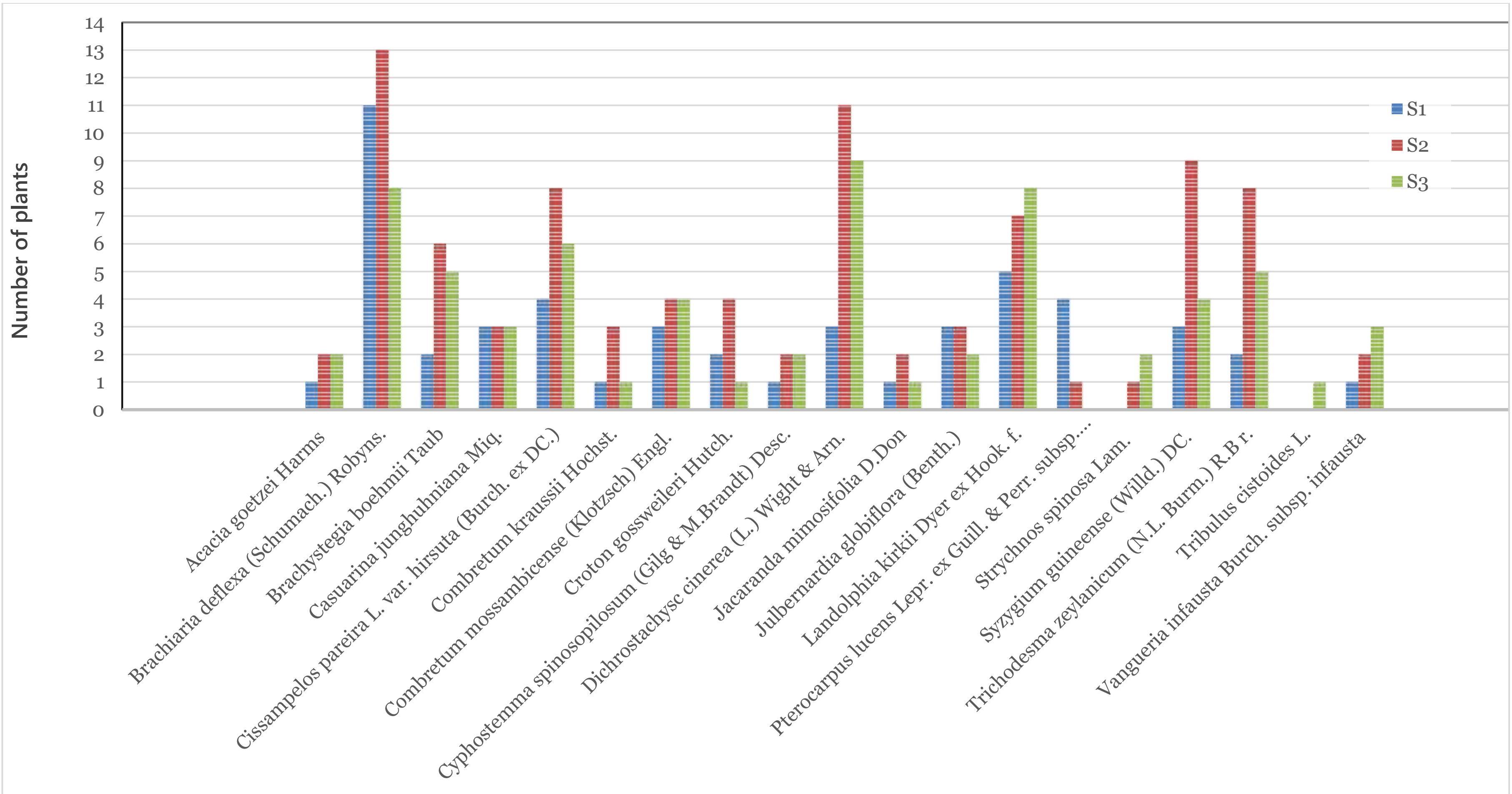


Figure 16: Number of species in sampled segments in downstream riparian section

The study found species that were not on the records of vegetation in NSR which is in conservation focus and research invitation. The limited regional and global distribution of most species found further shows the uniqueness and conservation value of riparian ecosystems (Table 19).

Table 19: Species global distribution

Species name	Distribution
Senegalia goetzei (Harms) Kyal. Boatwr. subsp *goetzei*	Angola, DRC, Ethiopia, Kenya, Tanzania, Mozambique, Zambia, Zimbabwe.
Brachystegia boehmii Taub	Angola, DRC, Tanzania, Malawi, Mozambique, Zambia, Zimbabwe and Botswana.
Casuarina junghuhniana Miq	Java, Lesser Sunda Isl., Thailand, Laos, Vietnam, Myanmar, trop. Africa
Cissampelos pareira L. var. *hirsuta* (Burch. ex DC.) Forman	Latin America, DR Congo, Tanzania, Angola, Zambia, Comors and Madagascar.
Combretum kraussii Hochst.	Mozambique, Swaziland and South Africa.
Combretum mossambicense (Klotzsch) Engl.	Angola, Botswana, Kenya, Malawi, Mozambique, Namibia, South Africa, and Zambia, Zimbabwe.
Croton gossweileri Hutch.	Angola.
Cyphostemma spinosopilosum (Gilg & M.Brandt) Desc.	Afghanistan, Algeria, Angola, Bangladesh, Benin, Botswana, Burkina, Burundi, Cabinda, Cameroon, Cape Provinces, Caprivi Strip, Central African Repu, Chad, China South-Central, Comoros, Congo, Djibouti, East Himalaya, Egypt, Eritrea, Ethiopia, Free State, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Gulf of Guinea Is., Gulf States, India, Iran, Iraq, Ivory Coast, Kenya, Kuwait, KwaZulu-Natal, Laccadive Is., Lebanon-Syria, Liberia, Libya, Madagascar, Malawi, Mali, Mauritania, Mauritius, Morocco, Mozambique, Myanmar, Namibia, Niger, Nigeria, Northern Provinces, Oman, Pakistan, Palestine, Rwanda, Saudi Arabia, Senegal, Sierra Leone, Sinai, Socotra, Somalia, Sri Lanka, Sudan, Swaziland, Tanzania, Thailand, Togo, Uganda, Vietnam, Western Sahara, Yemen, Zambia, Zaïre, and Zimbabwe.
Dichrostachys cinerea (L.) Wight Arn. subsp. *africana* Brenan Brummitt	Widespread in Africa including Mozambique, Cape Verde and Zanzibar; and Asia.
Flacourtia indica (Burm. f.) Merr.	Central Africa, China, Indonesia, Malawi, Madagascar, Mozambique, India, Sri Lanka, South Africa and Swaziland and Zimbabwe (reported to be widely distributed in Tropical Africa south to northern South Africa).

Jacaranda mimosifolia D.Don	Australia, southern Africa, Hawaii, south-eastern USA, southern South America, Kenya, Uganda and Tanzania.
Julbernardia globiflora (Benth.) Troupin	Botswana, Burundi, DR Congo, Tanzania, Namibia, Zimbabwe and Mozambique.
Landolphia kirkii Dyer ex Hook. f.	Democratic Republic of the Congo, Malawi, Mozambique, Tanzania, Zambia, Zimbabwe, Somalia and South Africa.
Pterocarpus lucens Lepr. ex Guill. Perr. subsp. *antunesii* (Taub.) Rojo	Angola, Botswana, Malawi, Mozambique Namibia, Zambia and Zimbabwe.
Strychnos spinosa Lam.	South Africa, Swaziland, Namibia, Botswana, Malawi, Mozambique, Zambia, Zimbabwe, Kenya, Tanzania, Uganda, D.R. Congo (Zaire), Gambia, Senegal, Guinea-Bissau, Guinea, Ivory Coast, Burkina Faso, Sierra Leone, Liberia, Togo, Ghana, Sudan, South Sudan, Cameroon, Nigeria, Equatorial Guinea, Central African Republic, Gabon, Congo (Brazzaville), Benin, Angola, Somalia, Ethiopia, Seychelles, Madagascar, Mauritius, La Runion, Comores and USA.
Syzygium guineense (Willd.) DC. subsp. guineense	Botswana, Namibia, Saudi Arabia, Senegal, Somalia, South Africa and Yemen.
Tribulus cistoides L.	Cape Verde, Eritrea Kenya, Mozambique, Tanzania, South Africa, Togo, Zanzibar, Madagascar, Mauritius, Kenya, Bolivia, Columbia, Ecuador, -Galapagos Islands, Peru, Venezuela, Papua New Guinea, New Caledonia, Marshall Islands, Kiribati, Guam, French Polynesia, Cook Islands, Western Australia, Queensland, Hawaii, Jamaica, Puerto Rico, South Wales, Australia, USA, Trinidad and Tobago, Puerto Rico, Panama, Mexico, Jamaica, Honduras, Guatemala, Grenada, Bahamas, Dominican Republic, Antigua and Barbuda, Anguilla, Taiwan, India, Sri Lanka, Indonesia, Yunnan, Hainan and China
Tapiphyllum velutinum Robyns	Burundi, Malawi, Mozambique, Zambia, Zimbabwe.
Vachellia davyi (N.E.Br.) Kyal. Boatwr.	South Africa

4.1.8 Community track memory of LULCC

Community consultative meetings gave the underlying causes of community degradation of natural sensitive ecosystems they recognise as lack of alternatives and reserve administration guidance (Table 20).

Table 20: Community reports on groundwater points and landscape ecology

	Question	Lisongole village	Ntimbo 1 village	Remarks
1.	Land use change near areas where they see wildlife	All respondent (100%) reported that there has been a big LULCC near communities; another group (39.5%) reported that there has been small change; and 5.3% could not be specific.	A big fraction (99.2%) reported that there has been a big LULC; and 33.3% reported small change.	Community recognizes LULCC in the area around them where wildlife share have habitats
2.	Seasonal vegetation patterns in valley areas	A good fraction of all respondents (46.3%) reported that the area had experienced seasonal valley vegetation availability changes; and 53.7% said they could not be specific on the question.	A small fraction of all respondents (39%) reported that the area had experienced seasonal valley vegetation availability changes; and 61% said they could not be specific on the question.	Different seasonal valley vegetation patterns around human settlement areas.
3.	General comment on LULC change around community settlement areas	All respondents (100%) reported an overall LULCC in areas around community settlement areas with 96.7% reporting more land clearance for agriculture has increased; and 6.5% reported increased area under human settlement areas.	All respondents (100%) reported an overall LULCC in areas around community settlement areas with 74% increase in total area under agriculture; and 26% reported increased area under human settlement areas.	Community members recognize LULC change
4.	Main drivers of LULC	All people (100%) reported change in seasons; and 72.4% reported human population growth for settlements.	All people (100%) reported change in seasons; and 82.1% reported human population growth for settlements.	Changes in seasons and LULC recognized by local communities

4.2 Objective 2: Establishment of rainfall runoff and water source areas

This section presents results of the analysis but discussion of this data can be found in the next chapter or complete details found in the published papers in Appendices. The papers were:

i. *Using SWAT model and field data to determine potential of NASA-POWER data for modelling rainfall runoff in Incalaue river basin*. Computational Water, Energy, and Environmental Engineering, **11**, 65-83. https://doi.org/10.4236/cweee.2022.112004

ii. *Mapping Landscape Positions and Relevance of Two Dambo-Springs in Incalaue River Basin in Niassa Special Reserve, Mozambique: Information for Drought Water Shortage Effects Management* Journal of Environmental Science and Engineering **B 10** (2021) 211-226. doi:10.17265/2162-5263/2021.06.001

4.2.1 Soil hydrologic properties

There was no specific uniform top soil physical properties during fieldwork classification apart from being stony and plant having roots (Table 21).

Table 21: Top soil physical characterisation

Plot location	A	B	C	D	E	F
Mottles (<wet zone>)	Yes	Yes	Yes	Yes	No	No
Granules (<wet zone>)	Yes	Yes	Yes	Yes	Yes	Yes
Stones (<wet zone>)	Yes	Yes	Yes	Yes	Yes	Yes
Biomass	Roots	Roots	Roots	Roots	Roots	Roots
Depth of top layer (m)	2.9	2.8	3.1	3.5	2.1	3.8

The soils were predominantly sandy and sand particle size was analysed (Tables 22 & 23).

Table 22: Soil physical properties

Code	dg (Bulk density)	%P (Porosity)	C (%)	Organic matter (%)	Sand (%)	Clay (%)	Silt (%)	Textural class
A1	1735.71	62.01	0.68	1.34	86.34	6.34	7.32	Loamy sand
A2	1721.52	54.15	0.19	0.37	87.93	9.17	2.90	Loamy sand
A3	1945.49	64.04	0.38	0.75	86.67	5.92	7.40	Loamy sand
A4	1725.15	71.29	0.24	0.48	82.49	10.21	7.30	Loamy sand
B1	1929.18	34.04	0.08	0.16	77.46	17.53	5.01	Sandy loam
B2	1958.55	41.78	0.08	0.16	81.11	12.11	6.78	Sandy loam
B3	1710.13	33.32	0.14	0.27	80.79	14.77	4.43	Sandy loam
C1	1831.80	24.31	0.05	0.11	76.24	19.39	4.36	Sandy loam
C2	1718.84	55.96	0.27	0.53	88.75	5.87	5.38	Sand
C3	1828.83	26.28	0.76	1.50	90.59	4.95	4.46	Sand
C4	1754.73	39.00	0.62	1.23	80.01	9.49	10.49	Loamy sand
C5	1726.67	32.07	0.33	0.64	82.54	10.98	6.49	Loamy sand
D1	1919.44	38.50	0.27	0.53	88.70	8.35	2.95	Loamy sand
D2	1926.57	39.07	0.27	0.53	87.97	8.66	3.37	Loamy sand

This kind of soil in this sloping landscape means more sedimentation and runoff.

Table 23: Soil particle size classes

Code	> 2mm	> 1mm	> 0.6 mm	> 0.25 mm	< 0.25 mm
A1	0.247	2.108	4.594	7.257	3.485
A2	0.07	1.202	3.503	7.359	6.087
A3	0.028	1.208	3.106	7.319	5.900
A4	0.1	1.079	2.557	6.21	7.023
B1	0.047	1.489	4.061	6.837	3.030
B2	0.017	0.946	3.467	6.946	5.366
B3	0.042	1.19	3.63	7.067	4.472
C1	0.028	1.379	3.739	6.982	3.598
C2	0.576	2.62	3.874	7.052	4.027
C3	0.211	2.789	5.249	6.903	3.147
C4	2.125	2.054	1.964	3.775	6.095
C5	1.406	2.302	2.521	4.28	6.105
D1	0.512	1.479	2.666	6.15	7.237
D2	0.038	1.489	3.444	7.55	5.764

All soil samples had particle sizes largely in the classes of >2.5 mm class which means high porosity and the lesser number of >2 mm shows sandy soil with smaller granules and this makes it to be prone to erosion and this explains high levels of sedimentation observed in the river channel. The uniformity of samples from different sampling sites was further assessed to make an estimation of deviations in distribution across the landscape using log-log plots (Figure 17). The results above showed that it is only sand content and bulk density that can related for all the sampling sites. The study results above interestingly show that FAO characterization of the soil misses the top-soil layers and characteristics and these are even most important on river flow generation, composition and quality.

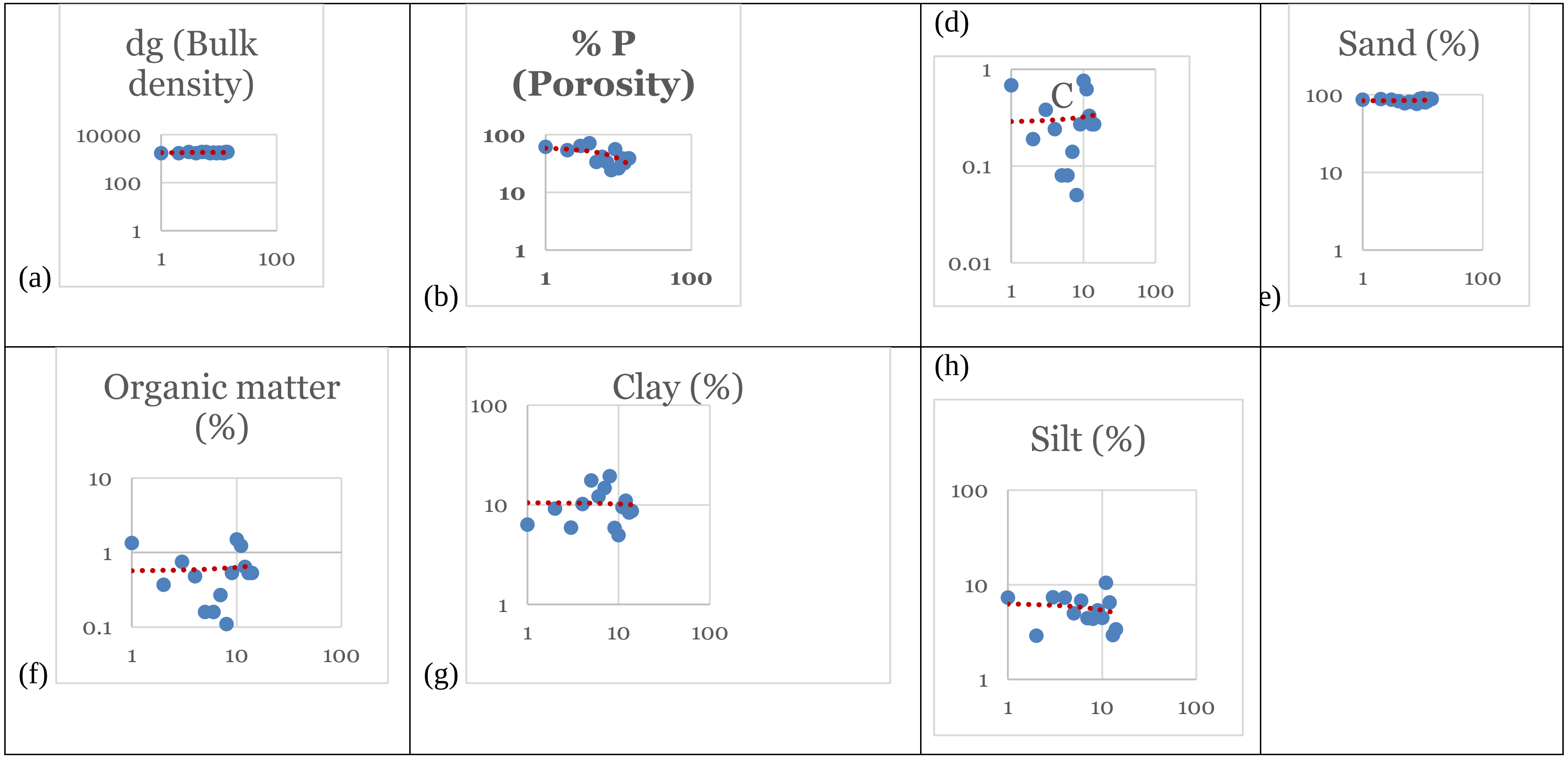


Figure 17: Log-log frame diagrams for soil parameters

Note: Each graph is logarithms of a parameter against sampling sites

4.2.2 Hydrologic Response Units (HRUs)

Understanding of water source areas in sub-catchments was additionally supported with characterisation of HRUs in vegetation classes to support LULC change impact as manifested in river flow changes. That was assumed reliable since the area is largely a wildlife reserve meaning less landscape change apart from vegetation change. The catchment has 20 dominant HRUs; and 241 individual HRUs across the sub-catchments (Figure 18). Four slope classes existed which were 0-3% (112 HRUs; 3-6% (141 HRUs), 6-9% (76 HRUs) and 9-99% (88 HRUs). A larger share catchment is in the 3-6 percent (52.65% of the area). There was notably 5.41% of the catchment in the 9-99% percent class which shows steep slopes. The distribution of HRUs by LULC was in the order of HDW (76) > LDW (74) > MDW (72) > WGL (70) > MFS (67) > IMP (28) > BULT (9) > RBA (8). The FAO soil data for the area was used since there is no soil data and the dataset gives a single soil type for the basin (Lf87-2-3b-776). Low Density Woodland had the largest number of single HRUs by area (31.44%).

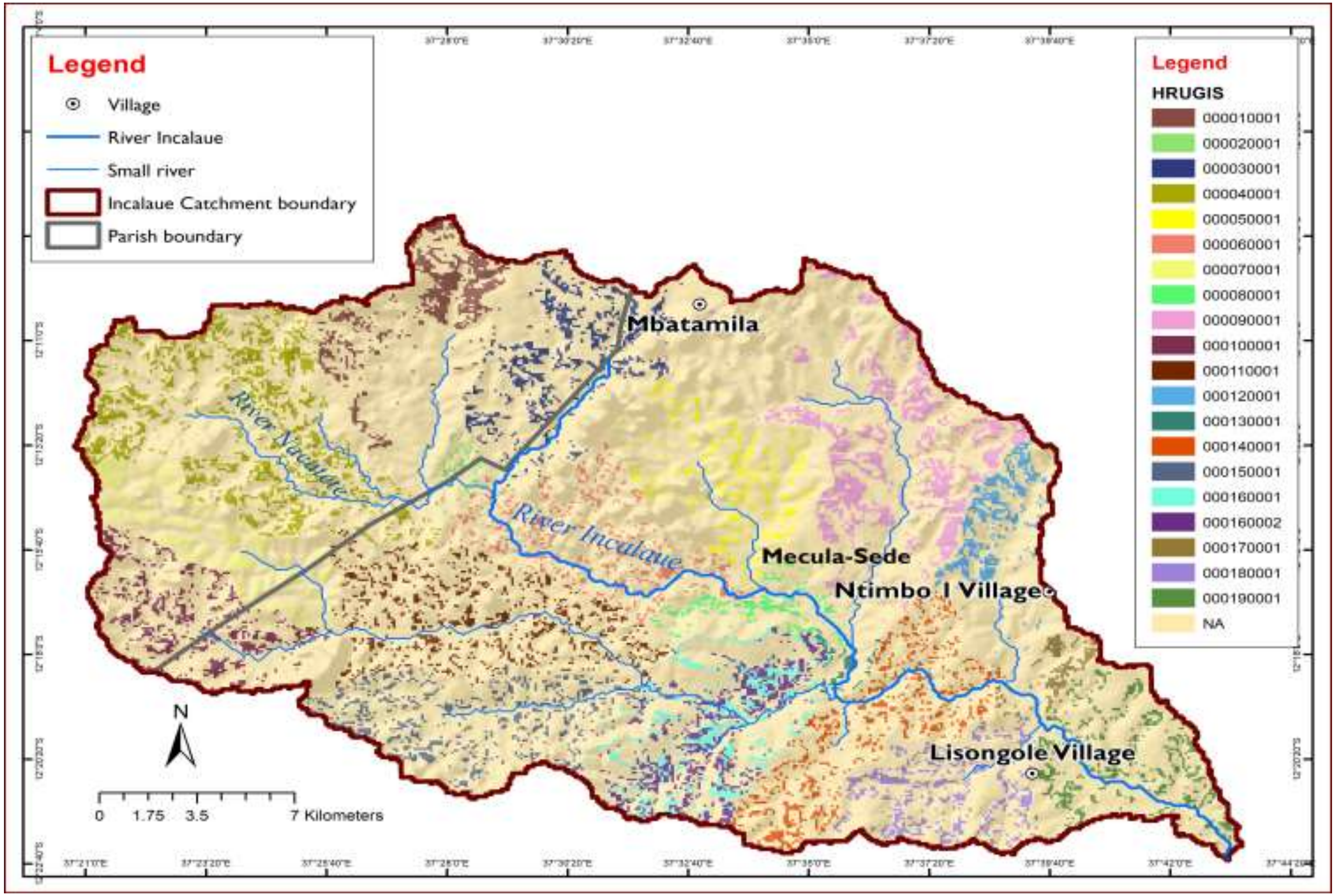


Figure 18: Dominant HRUs

The largest individual HRU was in Mountain Forest and the smallest in Medium Density Woodland vegetation classes (Table 24).

Table 24: Dominant HRUs (2021)

HRU GIS	LANDUSE- HRU_CODE	Area (ha)	%watershed area
10001	High Density Woodland --> FRSE/Lf87-2-3b-776/3-6	4359.3332	6.25
20001	Mountain Forests--> DEPF/Lf87-2-3b-776/3-6	444.3854	0.64
30001	Low Density Woodland --> WOOD/Lf87-2-3b-776/3-6	4956.2038	7.11
40001	Low Density Woodland --> WOOD/Lf87-2-3b-776/3-6	7476.1302	10.73
50001	Wooded Grassland --> BUSH/Lf87-2-3b-776/3-6	4111.8716	5.9
60001	Wooded Grassland --> BUSH/Lf87-2-3b-776/3-6	3919.3046	5.62
70001	Medium Density Woodland --> MWOOD/Lf87-2-3b-776/3-6	2633.2011	3.78
80001	Wooded Grassland --> BUSH/Lf87-2-3b-776/0-3	1574.5183	2.26
90001	High Density Woodland --> FRSE/Lf87-2-3b-776/3-6	8758.7483	2.57
100001	Low Density Woodland --> WOOD/Lf87-2-3b-776/3-6	3429.6094	4.92
110001	Wooded Grassland --> BUSH/Lf87-2-3b-776/3-6	5106.0749	7.33
120001	High Density Woodland --> FRSE/Lf87-2-3b-776/3-6	2665.4408	3.82
130001	Low Density Woodland --> WOOD/Lf87-2-3b-776/0-3	317.1692	0.46
140001	Wooded Grassland --> BUSH/Lf87-2-3b-776/3-6	4036.0647	5.79
150001	Wooded Grassland --> BUSH/Lf87-2-3b-776/3-6	3995.9829	5.73
160001	Low Density Woodland --> WOOD/Lf87-2-3b-776/0-3	2378.2706	3.41
170001	Wooded Grassland --> BUSH/Lf87-2-3b-776/0-3	2221.5536	3.19
180001	Medium Density Woodland --> MWOOD/Lf87-2-3b-776/3-6	719.73	1.03
190001	Mountain Forests --> DEPF/Lf87-2-3b-776/3-6	2971.2825	4.26

4.2.3 Rainfall-runoff relationship

Fieldwork collected data also showed a positive rainfall runoff relationship with seasons of no rainfall and no river flow periods; and little rainfall and no flow. The peaks river flows for the two years of fieldwork being from November up to May with the rainfall seasons following the same trend (Figure 19). During the gerall rainfall and river flow relationship, since the rainfall stations are not far apart the average daily rainfall was used.

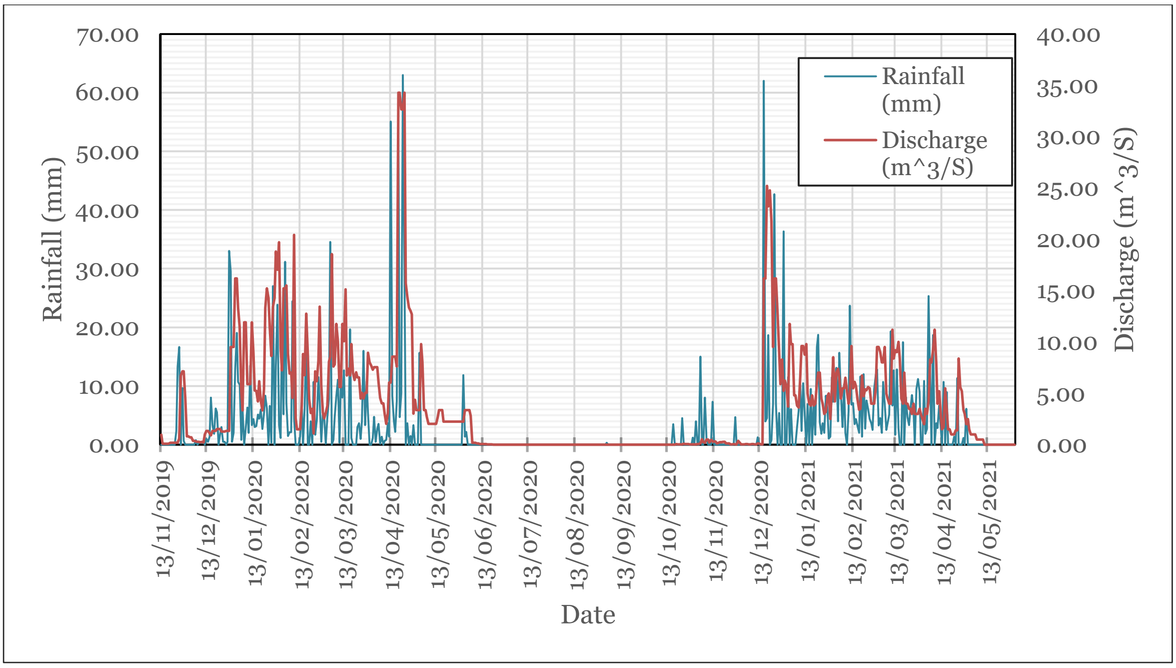


Figure 19: Daily rainfall-runoff patterns over the study time

Linear regression was used to test the rainfall and runoff relationship. Analysis gave a p-value for the overall F-test as 9.21E-37 which was less than 0.05. This means that the regression model is statistically significant and provides a good fit to the data.

	df	*SS*	*MS*	*F*	*Significance F*
Regression	1	4005.412	4005.412	185.7305	9.21E-37
Residual	564	12163.07	21.566666		
Total	565	16168.48			

The coefficient for rainfall runoff was 0.357. This positive coefficient means that as rainfall increases, river flow also increases. For every one-unit increase in rainfall (mm), river flow increases on average by 0.357m^3s^{-1} of the previous.

River flow	*Coefficient (β)*	*t-value*	*P-value*
Intercept	2.644 (0.215)	12.328	4.36E-31
Rainfall (mm)	0.357 (0.0262)	13.6283	9.21E-37**
Adjusted R^2 = 0.246, R^2 = 0.248, Multiple R = 0.498 and n=566			

The statistical significance level in asterisk (**) means p<0.05 at 5%. The values in parentheses ( ) are standard errors.

The P-value of 4.36E-31 supports rejection of a null hypothesis that there is no relationship between rainfall and river flow. Analysis was then done to individually explore the relationship between rainfall data at the different gauging station using multiple regression analysis.

Multiple regression results of rainfall and river flow

Variables	Coef.	Std Err	P-Value	95%	Conf. Interval
Lisongole	0.246	0.069	0.000	0.108	0.383
Ntombo_1	0.015	0.069	0.828	0.152	0.122
Mbatamila	1.232	0.561	0.000	1.121	1.341
Cons	0.271	0.192			

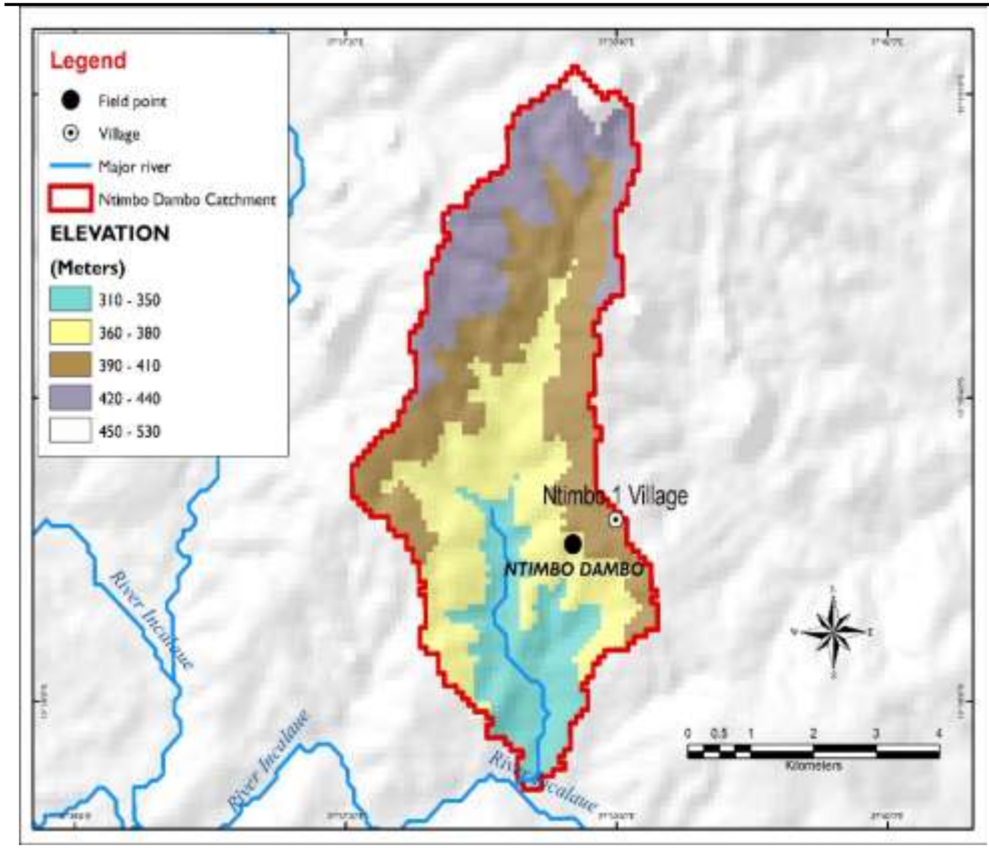
The results above showed a significant a strong positive relationship between the rainfall and river flow for Lisongole and Mbatamila (P<0.05). There was however an insignificant relationship between rainfall data from Ntimbo_1 rainfall station and river flow.

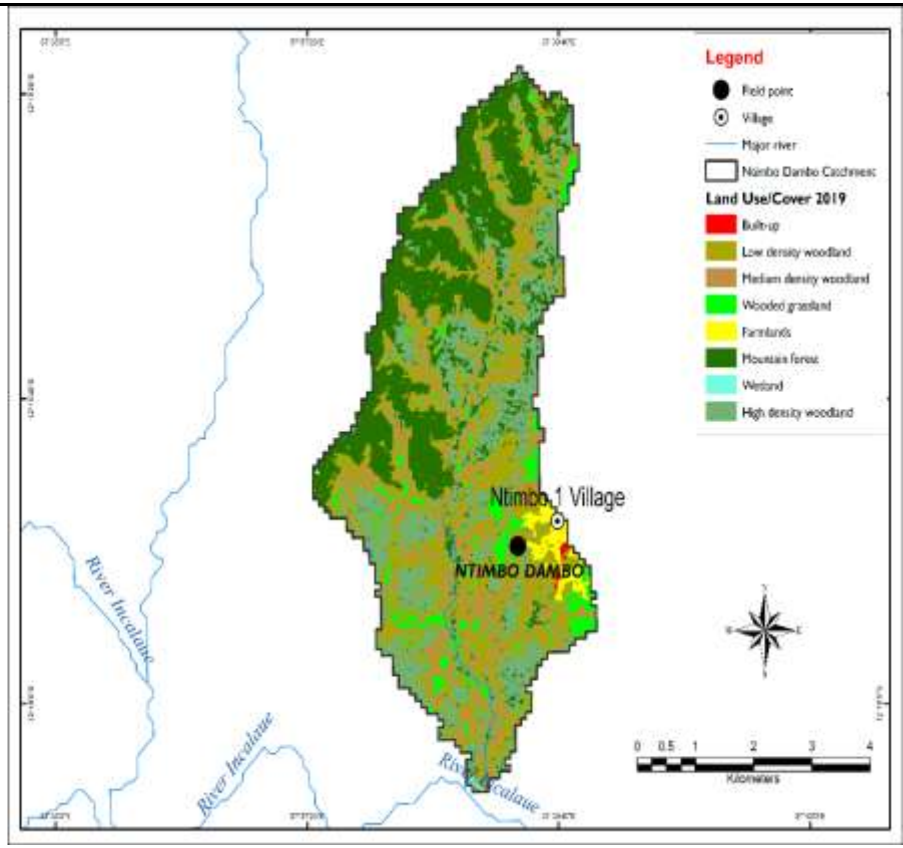
4.2.4 Dambo groundwater springs assessment as HRUs and water sources

4.2.4.1 Dambo ground spring catchments characterisation

There were two groundwater springs which were named dambos-springs because dambos were encompassed in their terrain derived micro-catchments. The names of the springs were given by the communities that were closely located. While Ntimbo spring had same name as the village, the Lisongole village spring was called “Lizongole”. Ntimbo 1 dambo spring micro-catchment (26.55 sq. km) has a bigger area compared to Lizongole dambo micro-catchment (1.33 sq. km). The Ntimbo 1 spring water flowed in an open stream in the southern direction in tree dominated vegetation strata in a sandy soil dominated area with large rocks. Lizongole drainage flows into a sedge dominated vegetation covering sandy-clay soil in a relatively flat terrain.

From LULC mapping, the Ntimbo 1 catchment has mixed LULC classes and a steep elevation gradient (Figure 20). The Lisongole dambo catchment equally had mixed LULC classes is located in the downstream flat area with all vegetation classes including a sedge dominated downstream section in the western side (Figure 21). The soil texture map has also developed from the Food and Agriculture Organization of the United Nations (FAO) dataset during the study (Figure 22). According to the above FAO mapping; and the only available official government records which could be accessed as a hardcopy map from (Instituto de Investigação Agrária de Moçambique (IIAM) and digitized, dambo-spring catchment areas have shallow soils and their texture varies. The area is covered by several textural classes and underlain crystalline shales on amphibolites and milinites basement rocks.

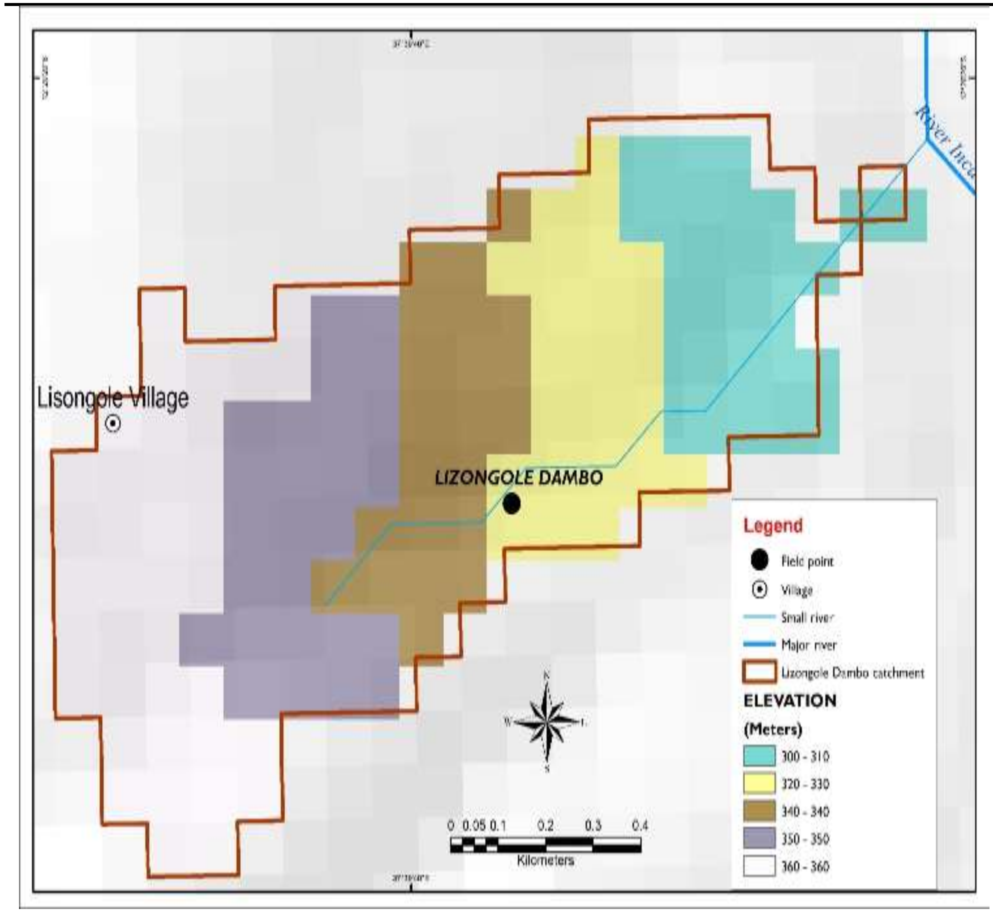




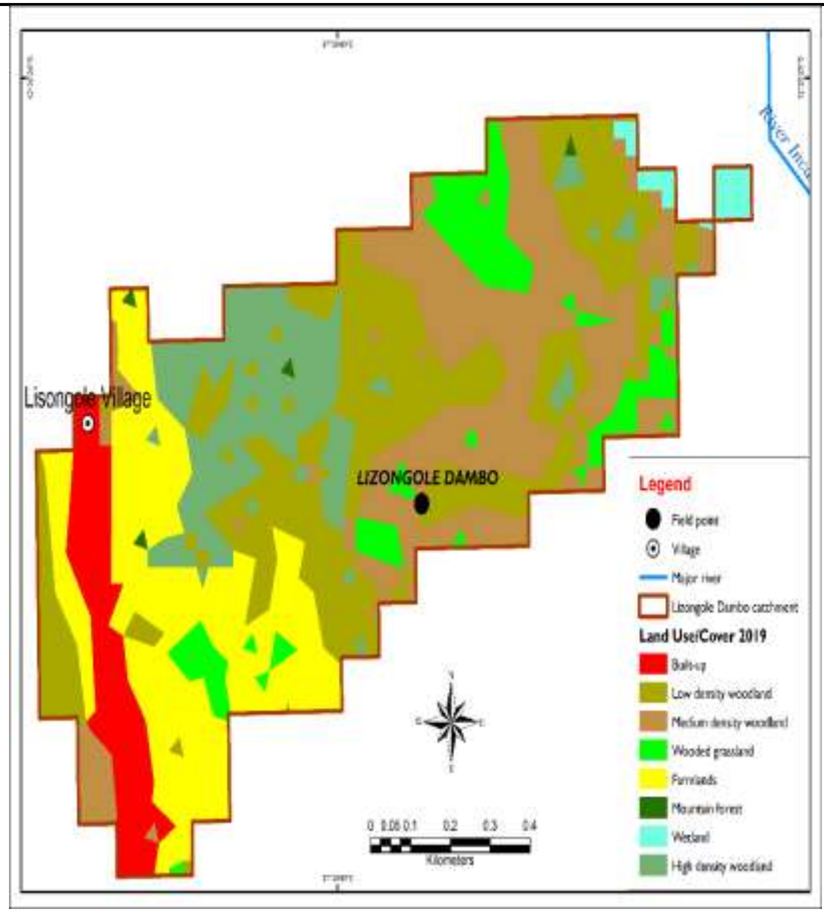
Topography | Land use/cover

Figure 20: Ntimbo 1 dambo spring micro-catchment LULC

The Lizongole dambo-spring catchment is located in the downstream flat area of Incalaue catchment with depleted tropical rain forests, cropland, grassland and settlements and wetland section in the western side (Figure 21).



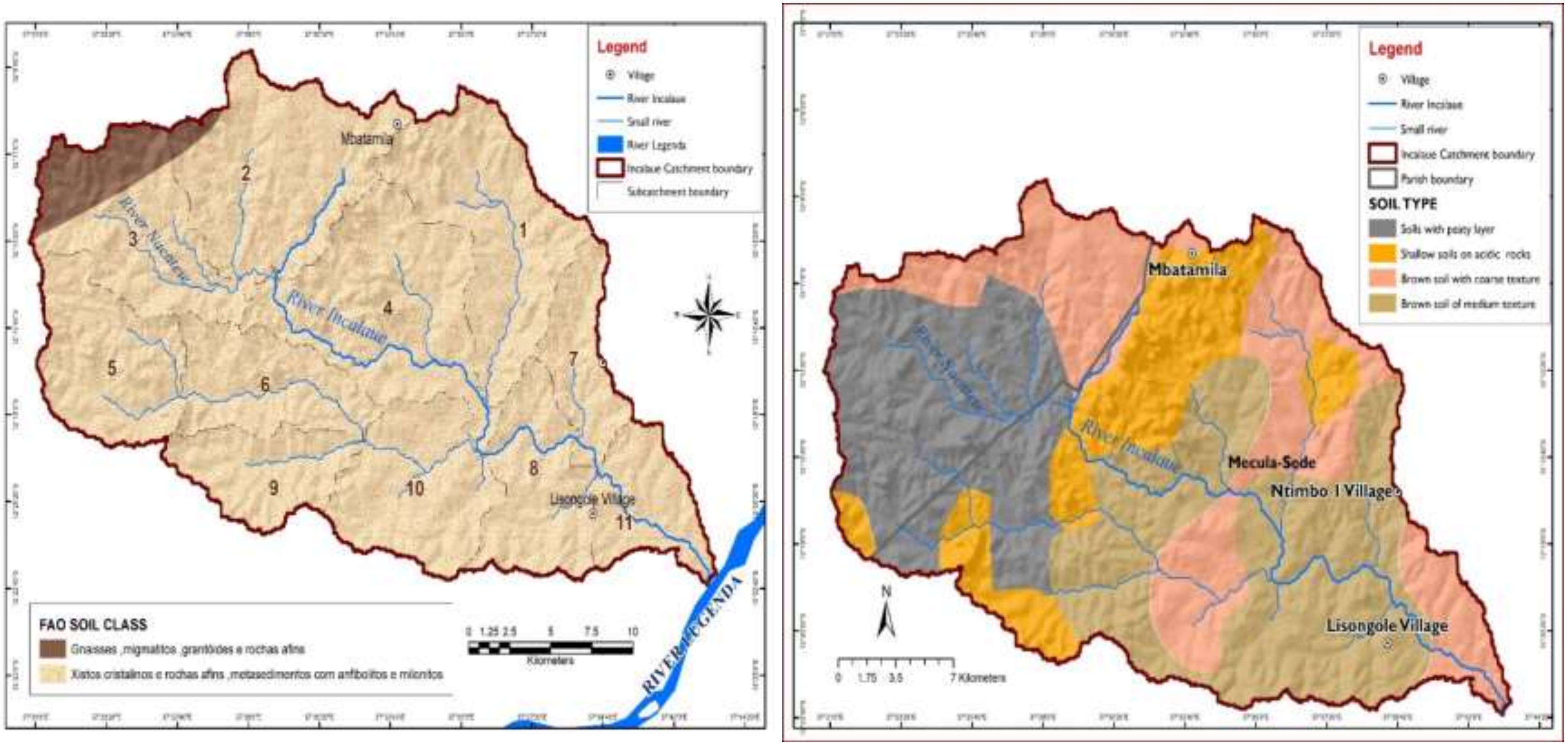
Topography



Land use/cover

Figure 21: Lizongole dambo spring micro-catchment LULC

The FAO dataset provided bed-rock and IIAM provided data was used for soil texture mapping (Figure 22).



(a) Basement rock (b) Soil texture

Figure 22: FAO soil type and soil texture maps of the basin.

Field observations and hand-feel of sample agreed showed that Lisongole spring micro-catchment had a single soil texture class (Figure 23)

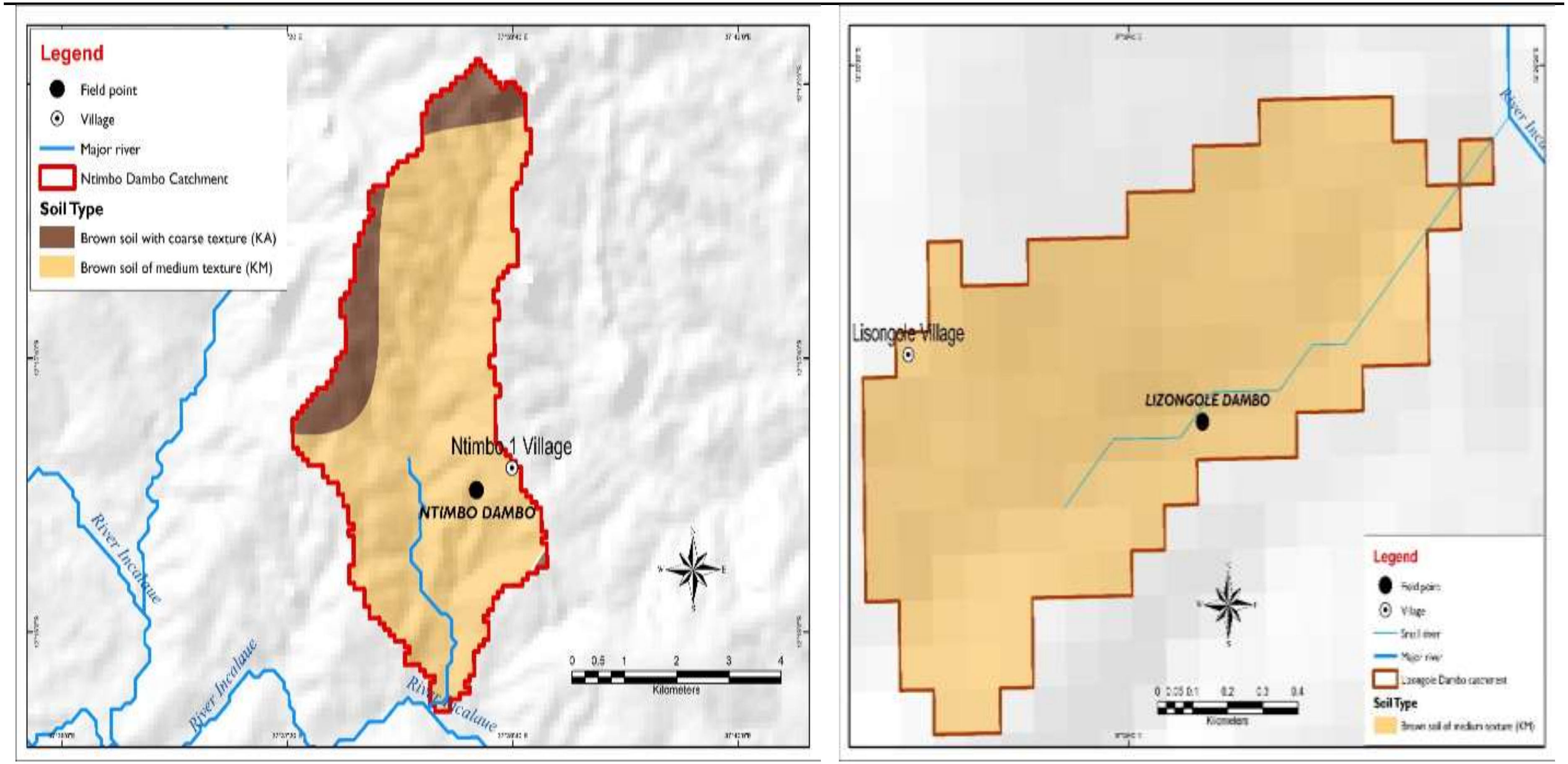


Figure 23: Soil texture maps

Lizongole micro-catchment albeit having a smaller area hosts more human population settlements (Table 25). This is possibly because of being more of flat area location compared to Incalaue catchment. Ntimbo spring catchment notably is partly covered by mountain forest unlike Lisongole catchment.

Table 25: Land use and land cover in the dambo spring micro-catchments (Sq. km)

Land use/cover in 2021	Ntimbo 1	Lizongole
Built-up	0.04	0.08
Low density woodland	6.73	0.31
Medium density woodland	4.26	0.27
Wooded grassland	1.56	0.08
Farmland	0.49	0.23
Mountain forest	7.17	0
High density woodland	6.27	0.14
Wetland	0.03	0.02
Total	26.55	1.13

4.2.4.2 Recharge characterisation of dambos springs

The Ntimbo 1 spring drainage water flowed in an open stream in tree dominated vegetation strata in the southern direction in an area with large rocks although with sandy soil; and Lizongole one flows into a sedge dominated vegetation covering clay-loam mud soil in a relatively flat terrain. No direct connection was observed but both spring dambo drainage water flowed in the direction of stream channel networks connected to river Incalaue. Springs gauging for yield measurements was done in September 2020 for 30 days in the middle of the dry season. Lizongole spring was not accessible in the wet season due to floods so measurement was only done for Ntimbo 1 spring in March 2021.

The groundwater spring micro-catchments were both accessible for the community during the dry season but only Ntimbo spring was accessible during the wet season. Ntimbo 1 spring flow was higher than the Lizongole one during the dry season. This study tested the difference in mean spring water yields in the dry season: Null hypothesis (Ho); was that there was no statistical difference ($\mu < 0$) and Alternative (H_1); there is a statistical difference ($\mu > 0$).

Variation between Ntimbo 1 and Lizongole spring yields

δmean =	0.0007	t = 16.6660608
Sδ =	0.000019	number of tails =1
n =	30	p = 1.29E-10
df =	29	

The p-value =1.29E-10 was statistically significant at 5%. Therefore the study rejected the Null Hypothesis (Ho) and concluded there was a statistically significant difference between the spring water yields in the dry season.

However, there was increase in water yield for Ntimbo 1 spring during the rainy season. This study tested the difference in daily mean spring water yields in the rainy and dry seasons: Null hypothesis (Ho) was that there was no statistical difference ($\mu < 0$); and Alternative hypothesis (H_1) was that there was a statistical difference ($\mu > 0$).

Variation in Ntimbo 1 spring yield

δmean =	0.00407	t = 53.020029
Sδ =	0.00034	number of tails = 1
n =	30	p = 2.06E-20
df =	29	

The p-value = 2.06E-20 was statistically significant at 5%. Therefore the study rejected the Null Hypothesis (Ho) and concluded that there was a statistically significant difference between the spring water yields in the wet and dry season.

4.2.4.3 Relevance for community and wildlife water provision

Lizongole basin albeit having a smaller area hosts more human population settlements possibly because of being more of flat area location compared to Lizongole catchment. Community consultations were used to assess experiences on seasonal changes and trends (Table 26). Attendance of these meetings was by 33 household heads in Ntimbo 1 and 38 in Lisongole and these were held in the dry season timing in the afternoons when people are not in gardens. There were 56 in Lisongole and 67 in Ntimbo 1 villages.

Table 26: Community reports on spring areas and water sources in the dry season

	Question	Lisongole	Ntimbo 1	Remarks
1.	Use of water from dambo springs at any time during the year	Yes (100%)	Yes (100%)	Community reliance on groundwater springs
2.	Presence of animals around the spring all year round	Yes (100%)	Yes (100%)	Wildlife dependence on dambo spring water points
3.	Time of the year that wildlife animals are most common	A small fraction (39.5%) said August to October; 55.3% said July to October; and 5.3% could not be specific	A big fraction (66.7%) said June to October; and 33.3% said April to August	Wildlife seen all time but mostly in the dry season.
4.	Other community water sources in the dry season	Dig water collection wells in the dry river sand (85%); and fetch from dambo spring water-collection well (100%).	Fetch water from dambo spring (100%)	Ntimbo 1 solely dependent dambo spring water-collection well

4.3 Objective 3: Establishment of effects of climate and LULC to river flow

This section presents results of the analysis but discussion of this data can be found in the next chapter or complete details found in the published papers in Appendices. These were.

I. Using SWAT model and field data to determine potential of NASA-POWER data for modelling rainfall runoff in Incalaue river basin. Journal of *Computational Water, Energy, and Environmental Engineering*, 11, 65-83. https://doi.org/10.4236/cweee.2022.112004

II. *Manuscript*: Understanding land use, land cover and climate effects on rainfall runoff source areas in Incalaue catchment, Niassa Special Reserve, Northern Mozambique Manuscript submitted to MDPI Sustainability Journal. https://www.mdpi.com/journal/sustainability.

4.3.1 Performance of auto calibrated SWAT model with FAO soil dataset

The applicability of SWAT model was tested to model hydrologic behaviour of the river by auto-calibration using WXGEN data assessed for period of 2001 to 2021 in preparation for analysis comparisons with NASA POWER data. Results of the model showed average monthly rainfall runoff for study period (2001 – 2021having high flows for months at the end of a year and start of the next year (Table 27) which is the situation that was observed in the area during fieldwork time period from (2019 – 2021).

The approach was used as an exploration of model auto-calibration for the research area which is a hard to area in the region. WXGEN dataset showed peak rainfall runoff for the study time being from December to April and low flows for the months of June to October. The above situation was observed during field work and shown in rainfall and river gauging. The model also confirmed the reduced river flow showing which showed river channel sedimentation in the wet season from sediment yield modelling.

The model showed a good correlation coefficient for monthly rainfall runoff (R^2 = 0.8) for the period 2001 – 2021. A coefficient of determination commonly known as R-squared (or R^2) is a measure of the amount of variance in the dependent variable that is explained by the independent variable. It shows the strength of a linear relationship between two variables and examines how the differences in one variable can be explained by the difference in a second variable.

Table 27: Monthly catchment hydrology indicator river flow indicator parameters

Month	Rainfall (mm)	Surface runoff (mm)	Lateral flow (mm)	Water yield (mm)	ET (mm)	Sed. Yield (Mg/l)	PET (mm)
January	310.28	86.33	0.29	100.04	86.91	5.33	110.56
February	296.7	92.82	0.36	142.1	89.73	5.64	101.69
March	271.05	66.25	0.48	150.58	108.24	1.35	116.95
April	103.71	13.77	0.43	97.42	91.52	0.13	115.27
May	20.46	0.2	0.33	55.22	73.34	0	125.11
June	8.24	0.04	0.23	23.2	49.98	0	122.83
July	6.74	0.01	0.19	5.03	28.33	0	137.41
August	7.41	0.02	0.14	1.56	13.89	0	161.27
September	4.74	0.01	0.11	1.08	6.81	0	192.13
October	13.61	0.09	0.09	0.91	10.98	0	200.28
November	55.28	3.33	0.08	3.79	25.75	0.08	176.19
December	189.01	20.27	0.15	21	65.61	0.61	133.58

There was a strong relationship between rainfall and river flow for the Incalaue catchment landscape using SWAT model with WXGEN meteorological and FAO soil datasets which is expected of rocky areas on a slope. The FAO soil database was also used in all sub-sequent modelling work in this research.

4.3.2 NASA-POWER satellite meteorological data

NASA-POWER data over the study time showed months December to April and the intensive rainy season; May, June, July, August and September as the extreme deepening dry season; and seemingly with standout events in October and November. The NASA-POWER meteorological data shows a good seasonal trend for temperature, relative humidity and rainfall again in support of potential reliability for the study area (Figure 24).

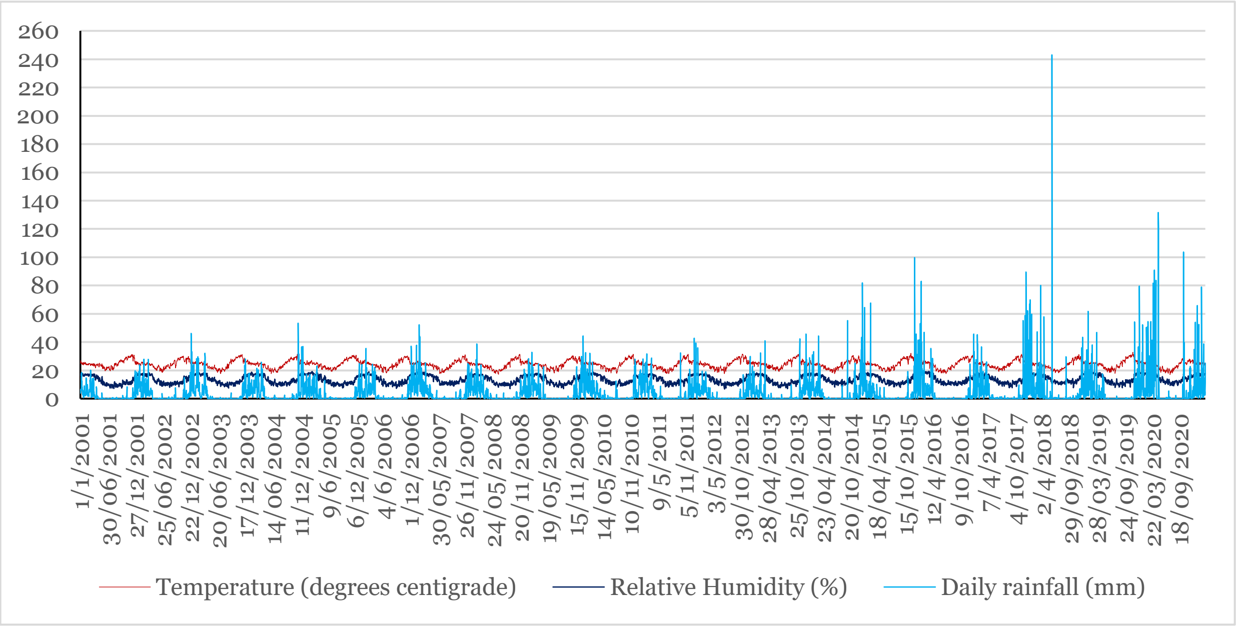


Figure 24: NASA-POWER daily meteorological data (2001 – 2021)

4.3.3 Comparing gauged and NASA-POWER rainfall data

In NASA-POWER satellite rainfall data, the months of June, July, August and September were the dry months as observed in the field. This also could be implied by the reduced river flow and channel sedimentation observed in the field were well expected gauging from NASA-POWER data. There was a good positive relationship between NASA-POWER and gauged rainfall for the study period (Figure 25). NASA-POWER data was however higher values than gauged data had especially for peak seasons.

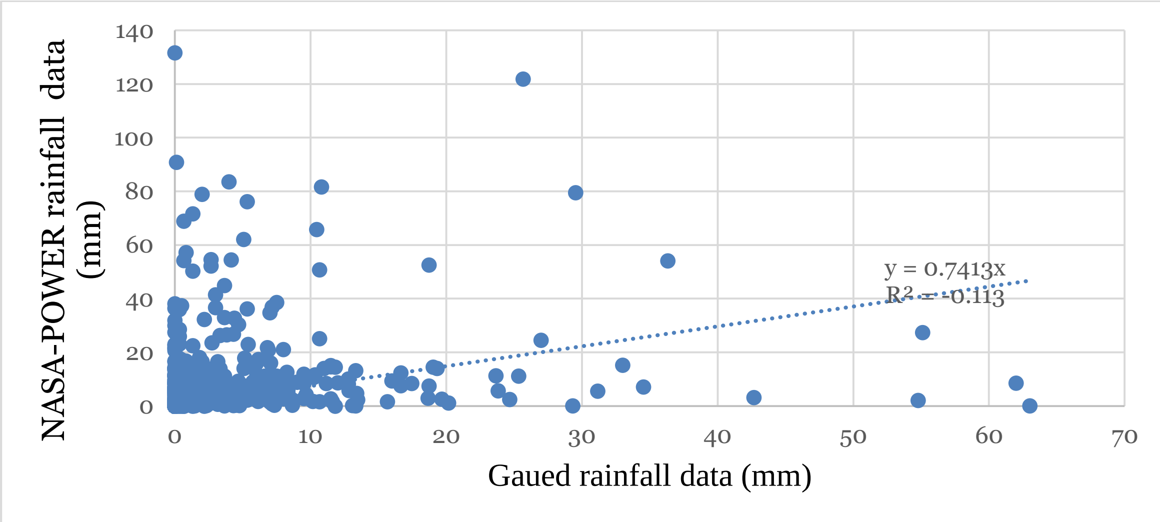


Figure 25: Comparing NASA-POWER and gauged daily rainfall data[1]

4.3.4 NASA-POWER satellite data derived rainfall-runoff relationship

NASA-POWER rainfall data generated a good monthly rainfall runoff relationship for the study period 2001 up to 2021 and this is taken to equally represent by relationship during fieldwork time as expressed in model performance (Figure 26).

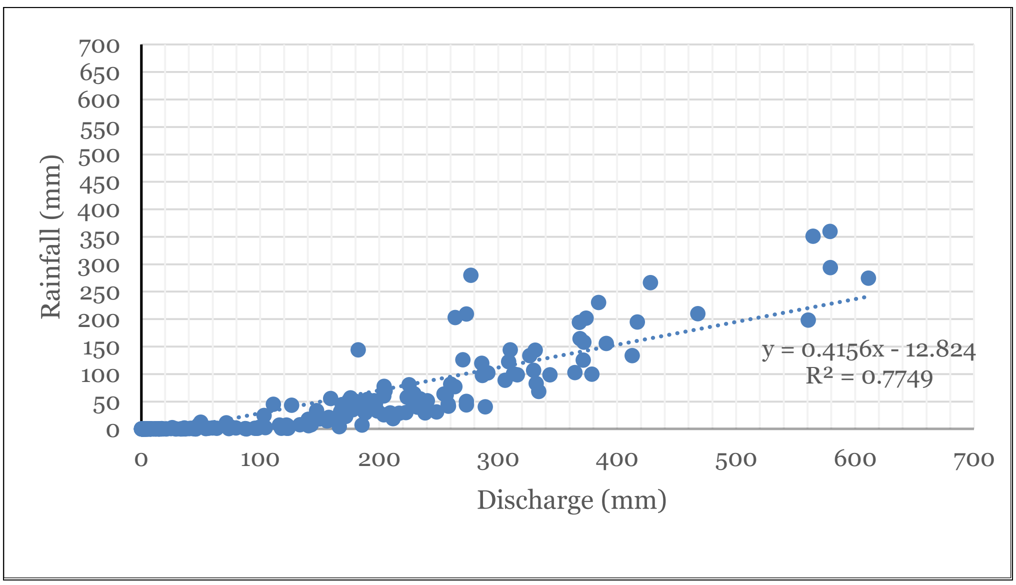


Figure 26: Monthly rainfall runoff model using NASA-POWER data (2001-2021)

[1] One outlier on 6/03/2018 was removed when generating this figure

There were seasons of high rainfall and high runoff; no rainfall and no river flow periods; and those of little river flow and no rainfall all of which appear in rainfall runoff modelled using NASA-POWER data.

4.3.5 Performance of SWAT model using fieldwork collected data

The seasonality in rainfall was matched with river flow both for observed and modelled rainfall runoff data (Figure 27).

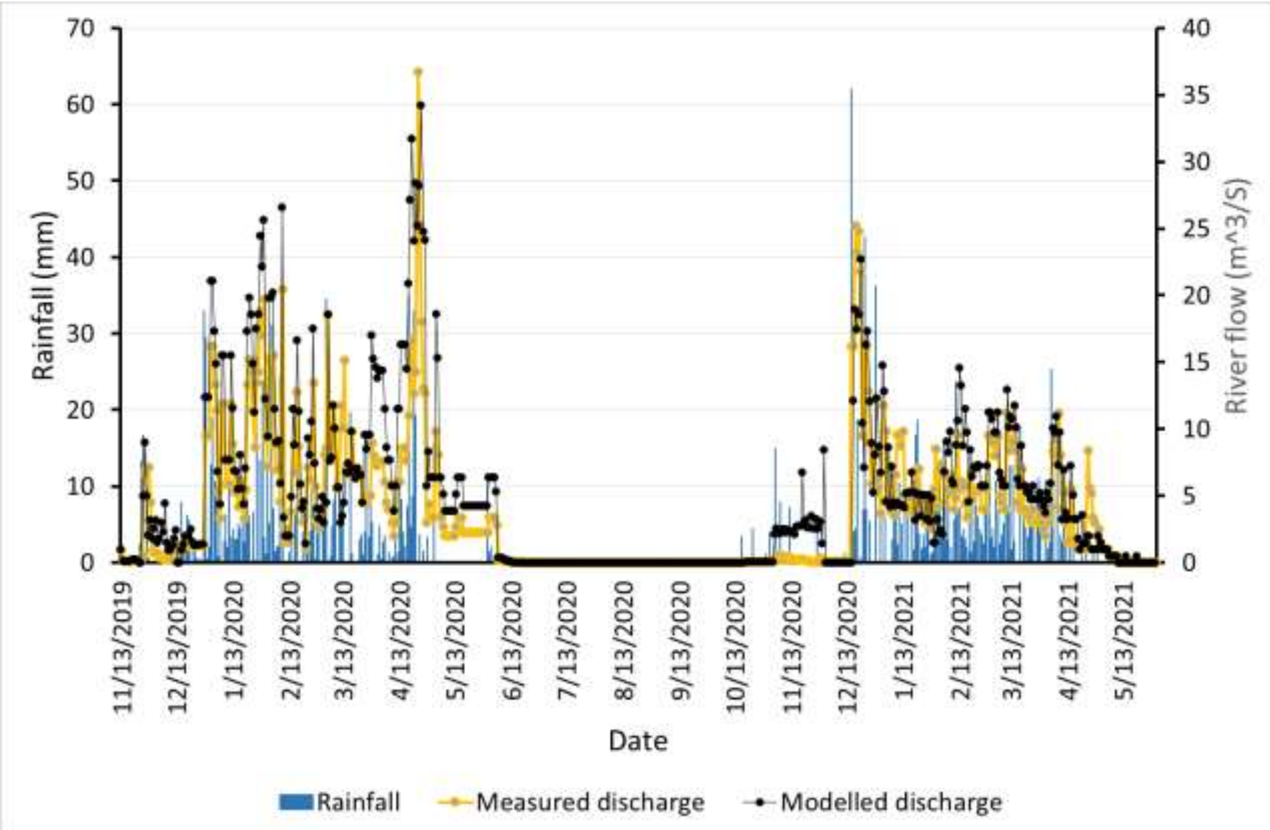


Figure 27: SWAT model calibration with fieldwork collected data

There was a good relationship between observed and predicted river flow (with gauged rainfall) which gave a Nash Sutcliffe Efficiency (NSE) of 0.677 and Root Mean Square Error (RMSE) of 0.193. The normalised RMSE for the data is 0.193 which shows that the model was successful.

4.3.6 Relative contributions of land use/cover and climate to river flow

The SWAT WXGEN and NASA-POWER climate data for the study period (2001 – 2021) both showed repetitive seasonality patters in rainfall runoff with wet season starting in November and ending in April which and this was replicated in gauged data (2019 - 2021). This study depended on this to use NASA-POWER data to model partial (fractional) contribution of climate and land use on rainfall runoff. Classification for LULC for the each of the studied years and NASA-POWER meteorological data was used. Four (4) SWAT models were built and used for modelling the four scenarios (Table 28) to model the effect of land use/cover and climate on rainfall runoff and this was done double to match comparisons in LULC sections of this research. Results show that there have been slight changes in river flow, predominantly caused by land use change. The results of simulation shows that the slight increase in rainfall runoff was in the months of peak-river flow except for a slight decline in February.

Table 28: Land use and climate effects on monthly river flow (m^3/s)

	Fixed land use		**Fixed climate**		**Effects on flow**		
	2001-2009 (S1)	**2010-2021 (S2)**	**2001-2009 (S3)**	**20101-2021 (S4)**	**ΔQC**	**ΔQ**	**ΔQL**
	L1C1	**L1C2**	**L2C1**	**L2C2**			
January	124.97	133.08	134.82	148.21	10.75	23.24	12.49
February	118.92	111.62	88.42	118.72	11.50	-0.20	-11.70
March	83.83	77.41	42.43	89.00	20.07	5.17	-14.91
April	19.50	24.78	21.29	23.13	3.56	3.64	0.07
May	12.71	24.74	20.41	25.49	8.56	12.78	4.23
June	1.50	0.50	0.50	1.50	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00	0.00
August	0.50	0.50	0.50	0.50	0.00	0.00	0.00
September	0.50	0.50	0.50	0.50	0.00	0.00	0.00
October	0.05	0.52	0.13	0.50	0.42	0.45	0.03
November	1.39	16.14	11.14	18.42	16.01	17.03	1.02
December	49.33	65.23	52.14	67.74	15.75	18.41	2.66

The simulated runoff declined mostly in the month of February over the study period (0.17%). There were notable increases in monthly flows for the months of October (0.45m^3/s), November (16.01 m^3/s), November (17.03 m^3/s), December (18.41 m^3/s) and January (23.24 m^3/s).

Coefficients [a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.	Correlations		
		B	Std. Error	Beta			Zero-order	Partial	Part
1	(Constant)	29.607	33.724		.878	.385			
	Land use	3.657	15.474	.035	.236	.814	.035	.035	.035
	Climate	2.219	15.474	.021	.143	.887	.021	.021	.021

a. Dependent Variable: Monthly river flow

The above analysis showed that both climate and land use have had insignificant impact on river flow. The analysis equally shows that their partial contribution is small (0.35 and 0.21) respectively.

CHAPTER FIVE

DISCUSSION AND CONCLUSIONS

5.1 Discussions

5.1.1 Assessment of land use and land cover in rainfall-runoff source areas

The study successfully combined land use classification, geographical characterisation of the area, river flow and groundwater community water source areas to examine assessment studies to make reliable inferences to water source areas This study contributes knowledge that can be useful to guide management in conservation of water resources connectivity in protected areas through habitat corridors ecosystem classification within their climatic niches in the Selous-Niassa trans-frontier conservation area which was identified as a necessity (Zella et al., 2018). The study collected data in the end rainy season and end of dry season which are the appropriate months of animal migration in the dry-humid climate for a seasonal river tributary in this wildlife reserve (Purdon et al., 2018a).

Vegetation classes like WGL spread across the sub-catchments can be attributed to favourable climate and space availability in canopy openings for wooded vegetation. The increase in taller vegetation class types is perhaps due to conservation efforts in this reserve area also hosting human settlement. This is a good environmental conservation achievement of efforts in this region where there is vegetation cover reduction and degradation due to anthropogenic activities widely reported (Muller et al., 2007). The change of vegetation cover in the study time towards higher cover levels was pronounced with LDW with grasslands as the main losers; and LDW and HDW means vegetation succession towards stable rainfall runoff contributing areas. There are indications of vegetation distribution in relation with topography, soil factors and human influences on rainfall runoff with sub-catchment 3 having the highest LDW cover and no human settlements.

In context of the study area being wildlife reserve with human settlement areas and land use, this study showed the need for LULC management to protect water sources especially for wildlife. This study adds specifics and detail on the need to conserve water resources connectivity in protected areas migration habitat ecosystem corridor within their climatic niches in the Selous-Niassa trans frontier conservation area which has been a knowledge gap (Zella et al., 2018). The study collected data in the end rainy season and end of dry season which are the appropriate months of animal migration in the dry-humid climate for a seasonal river tributary in this wildlife reserve (Purdon et al., 2018b; Zella et al., 2018). The study showed need for a plan for human LULC away from wildlife vegetation hotspot areas; identification and consideration of area-demanding threatened species that require landscape scale conservation; and prevention of degradation and loss of water source hotspots for wildlife as well as conservation of sensitive and localized vegetation species.

The increase in taller vegetation class types over the study period is perhaps due to conservation efforts in the reserve. This is a good environmental conservation achievement of efforts in this region where there is vegetation cover reduction and degradation due to anthropogenic activities widely reported (Zella et al., 2018).

There are indications of vegetation distribution in relation with topography, soil factors and human influences with sub-catchment 3 having the highest low-density woodland cover and no human settlements. Recently burnt areas in the landscape are mostly close to human settlement area. Mountain forest vegetation losses in human settled conservation areas have also been reported in miombo woodlands in Gorongosa National Park in central Mozambique (Muller et al., 2007). The relief variations and unevenness of elevation causes differences in soil depth and soil moisture and uneven distribution of mountain forests (Müller et al., 2012).

The main vegetation classes found were expected although some species were not on record for studies that were accessed for the NSR (Ribeiro et al., 2016; Ribeiro et al., 2013; Ribeiro et al., 2008a). Some vegetation assemblages are quite discrete, such as the mountain forest, but others overlap considerably, such as low-density woodland, medium density woodland and wooded grasslands. This study picks out the high moist rainfall mountain forests miombo vegetation class which was also reported for the region in the First National Report on the Conservation of Biological Diversity in 1997 (Ministry for Coordination of Environmental Affairs (MICOA), 1997). The largest decreases are for wooded grasslands (71.84%), wetlands (11.2%) and recently burned area (3.79%) which shows vegetation change towards taller vegetation and open areas in the season. A 0.9% woodland loss in NSR had been previously reported between 2001 and 2014 and was largely attributed to expanding agriculture around settlements and along main roads (Allan et al., 2017). Incalaue basin hosts communities in communities of Ntimbo 1 and Lizongole and is located is near to Mecula town, so potential community vegetation harvesting and degradation may be impacting on vegetation cover.

The study showed that landscape hydrology indication of sensitive vegetation land cover zonal areas in of seasonally sensitive dambo springs water source areas which are necessary conservation hotspot areas. This added information to studies on LULC that gave indication of vegetation representation of landscape hydrology; and added recommendation of environmental management areas in NSR. This affirms previous research which showed that it is important to identify zones and spatial typologies in physical geography, because it is the base of geographic classifications, applied in landscape descriptions and in spatial analyses (Moura & Fonseca, 2020). That study (in preceding sentence) showed that in landscapes, vegetation cover at topographical-soil zones forms hydrotopes during HRU mapping in the area where this study was done. These hydrotopes represent units of variations of lateral (interflow); and vertical processes (soil moisture, infiltration and evapotranspiration) and can be visualized in soil and vegetation patterns (Sprenger et al., 2018; Vorobevskii et al., 2020).

5.1.2 Establishment of vegetation representation of landscape connectivity

There was indication from vegetation distribution influence by topography, soil factors than human influences. Sub-catchment 3 has the highest low density woodland cover and no human settlements. Only sub-catchment 4 is largely covered by inselbergs with mountain forests mostly on its eastern side neighbouring with sub-catchment 5. The relief variations and unevenness of elevation causes differences in soil depth and soil moisture which explains the uneven distribution of mountain forests forest (Müller et al., 2012)

The main vegetation dominantly woodland vegetation types as expected in NSR were found by this study (Desmet, 2004; Ribeiro et al., 2013, 2016; Ribeiro et al., 2008). Soil hydraulic factors varied more even than vegetation which shows of need to assess other soil factors in relationship to vegetation patterns. Soils on acidic rocks did not dominate for any vegetation cover which agrees with literature (Moriarty & Honnery, 2008). This study contributes answers to the call to conserve connectivity based on landscape research in protected areas through habitat corridors ecosystem classification and protection so as to enable species migration within their climatic niches in the Selous-Niassa trans-frontier conservation area (Booth & Dunham, 2016; Winsor, 2019).

The existence of all types of vegetation in upstream in an ISL dominated area can possibly be attributed to weathering and erosion processes in the possibly young geology which research is needed on geology of the area. The low values of NDVI found with minimum of 0.040816 maximum 0.37 can be attributed to the area rocky nature of the landscape with dense vegetation widely interspersed with WGL. Both the highest and lowest NDVI values were for image of 2009 and were accompanied by higher values for images of 2001 and 2021, which may be attributed to times of image capture in this dry mid-climate season in this area with vegetation shedding leaves during the dry season.

There are indications of vegetation distribution in relation with topography, soil factors and human influences with sub-catchment 3 having the highest LDW cover and no human settlements. Recently burnt areas in the landscape are mostly close to human settlement area. There is MFS vegetation losses in human settled conservation areas which has been reported in Miombo woodlands in Gorongosa National Park in central Mozambique (Timberlake & Chidumayo, 2011). The nature of the landscape with unevenness of elevation causes soil accumulation in valley areas and differences in soil depth and soil moisture and hence uneven distribution of MFS (Ministry for Coordination of Environmental Affairs (MICOA), 1997).

The main vegetation classes found were expected although some species were not on record for the NSR (Boyd et al., 2010; Cowles et al., 2018; Tan et al., 2017). Some vegetation assemblages are quite discrete, such as the MFS, but others overlap considerably, such as LDW, MDW and WGLs. Efforts that have been made to do vegetation classification for the reserve have been found similar classes (Ribeiro et al., 2016; Spalding-Fecher et al., 2016). It was noted that there was a significant research gap in the Incalaue landscape on vegetation cover change classification given the type of land use and this study provided information (Murat Özyavuz & Özyavuzen, 2013; Ribeiro et al., 2016).

The study picked out the high moist rainfall MFS Miombo vegetation class which was also reported for the region in the First National Report on the Conservation of Biological Diversity in 1997 (Ministry for Coordination of Environmental Affairs (MICOA), 1997).

This research found that largest vegetation cover area loss was WGLs (71.84%), WETs (11.2%) and RBA (3.79%). There largest gains were ISL (111.18%) MDW (51.07%) and interestingly MFS (36.17%) which shows vegetation change towards taller vegetation and open areas. An overall 0.9% woodland loss in NSR had been previously reported between 2001 and 2014 and was largely attributed to expanding agriculture around settlements and along main roads (Allan et al., 2017). Incalaue catchment hosts communities in human settlement area of Ntimbo 1 and Lisongole so potential community vegetation harvesting and degradation may have an impact on vegetation-cover.

It has been shown that biomass production in NSR is significantly related to climate, which mainly means annual rainfall, and it thus is susceptible to disturbances (Pan et al., 2017). The results show need for land use management to promote conservation by highlighting changes in vegetation cover over study time especially vegetation loss and for climate change effects mitigation (Ramachandra et al., 2018). In context of the study area being wildlife reserve, this study showed proposes landscape hydrology monitoring as an approach to land use management. Spatial and temporal trend analysis of land use and LULC done in this study can be useful in landscape environmental conservation for indicator based impact management for changes in hydrological processes underlying vegetation diversity patterns.

In 1995, the Mozambique NLP (National Land Policy) was approved and the Land Law formulated in 1997. The NLP established a clear rights-based approach to freely guarantee land for Mozambicans and supporting rural community land rights thus opening up restricted landscapes with vegetation areas to possible degradation. Currently, land tenure rights are given as Direito de Uso e Aproveitamento da Terra (DUAT), a state-granted land right. The DUAT can be acquired in three ways, which are long-standing occupancy; customary occupation of the land by individual persons and by local communities; and based on good faith to individual national persons who have been using the land in good faith for at least ten years. This process of land acquisition is silent on protection of wildlife conservation areas. There is potential risk of environmental degradation due to human encroachment in the future due to population growth and expansion of the existing communities. This study further shows that there is need for identification and management of biodiversity hotspot areas as state institutions focus on the conservation as well as socio-economic developmental as has previously been identified.

5.1.3 Explanation of rainfall runoff relationship

The rainfall runoff model showed that the variation in river flow is explained by rainfall. This study provides a good start for future hydrology studies as the is particularly given that the area is data-poor with most research there only on LULC (Allan et al., 2017; Ribeiro, Matos, Moura, Washington-allen, et al., 2013). The study contributes to other studies on NASA-POWER data assessment and particulary works with an ungauged basin with success in rainfall runoff relationship in the region (Ngurah et al., 2022; Rodrigues & Braga, 2021). In this study NASA-POWER rainfall estimations were found to follow the same pattern like gauged daily rainfall data in the catchment but with higher values overall which translate to expectedly similar relationship in river flow modelling. This difference in river flow modelled and gauged data can be attributed to the nature of the landscape and gauging time being short (Jumani et al., 2019; Piniewski et al., 2018). The relationship between rainfall and river flow could also have been affected in gauged data because the study lacked automated river flow gauging. The sloppy landscape in most parts can also mean the records of river flow didn't capture the flash floods during some parts the day but rain gauges on the dry land collect good data. This challenge was also observed in RMSE of 1.98 which when normalised was 0.193 and NSE of 0.677. Those two performance measures showed the model was good but not very significant relationship. The value of NSE represents the relative magnitude of residual variance relative to the observed data variance. Its value ranges from $-\infty$ to 1 and a NSE value of ≥ 0.65 is considered acceptable (Makumbura et al., 2022). Similarly, RMSE indicates the magnitude of the errors in simulation by the models. An RMSE value of 0 is ideal; however, one of less than half of the standard deviation of the observed runoff are acceptable (Moriasi et al., 2015).

5.1.4 Examination of groundwater source areas and risks from LULC

The study showed no statistically significant difference in spring flow yield between the dry and wet seasons. The study on the other side showed that groundwater contribution to water availability for people and animals is very important especially in the dry season and their catchments areas are threatened by land use. There was no significant change in spring yields during the wet season but the little increment shows potential groundwater recharge in the area and a need for land use management to avoid any effects of recharge shift (Afzal & Ragab, 2019; Smith et al., 2016).
However, an increase in spring flow during the wet season shows the influence of sub-surface flow so land use management is support eventual spring yield deeper into the dry season. The Lisongle sandy valley dambo area gets wetter and impassable during the wet season but with spring stream has little water flowing in the dry season. There was higher increase in yield for Ntimbo 1 spring during the rainy season but a $p = 2.06E\text{-}20\%$ probability shows a statistically significant difference in spring flow yield between the dry and wet seasons ($p>0.5$).
The Ntimbo dambo spring has a longer catchment shape and a high elevation gradient (310m – 530m); and has small patches of lowland depression areas spread towards the eastern side. This shows rainfall runoff contribution to the river take longer while water is held in the catchment for people and wildlife. The Lisongole dambo spring catchment on the other side is shorter in width and in a flatter area (300-360 m), with lower vegetation and human a settlement area comparatively

away from the dambo. The situation in Ntimbo dambo spring catchment means less competition for water with animals compared with the Lisongole dambo. The situation in Ntimbo dambo catchment equally means a need for land use management efforts to protect the wetter areas for people and wild life given there were farmlands in dambo ecosystem.

5.1.5 Lessons from contributions of climate and LULC to river flow

It has also been previously reported that biomass production in NSR is significantly related to climate mainly mean annual rainfall and thus is susceptible to disturbances (Ribeiro et al., 2008a). Confirmation of the same by the results of this study showed need for land-use management to promote conservation by highlighting changes in vegetation cover over study time and for projected climate change impacts in Mozambique marked with increase in temperature and reduction in precipitation (Artur & Hilhorst, 2012; Spalding-Fecher et al., 2016).

This study agrees with the above studies by showing that both climate and land use have had insignificant impact on river flow. Although this study shows insignificant contribution of both, LULC still has the highest contribution (0.35 and 0.21 respectively). This gives an indication that rainfall runoff proportion and river flow behaviour is controlled by other factors most likely by slope since the area is hilly. Water availability in the river in the dry season remains in water pools trapped because of sand deposits at different rock. This shows that a very small of water is trapped in the catchment to contribute to water balance and the effect can was found in vegetation cover mainly dominated by taller trees and less of grass and lower vegetation for a longer part of the year.

Secondary data that was accessed from MICOA for northern Mozambique showed significant changes in monthly rainfall as well as minimum and maximum temperature. There is a climate projection tendency in the region towards increased annual temperature (2011-2100) in Niassa Province, where variations will be Tmax (0.92 to 4.73 ◦C), Tmin (1.12 to 4.85 ◦C), and Tmean (0.99 to 4.7 ◦C) respectively (Mavume et al., 2021). There are projected changes in mean monthly rainfall that do not translate to substantial changes in annual rainfall in the Niassa region. Projections range from -15 to +20mm per month, or -15% to +34% with differences caused by peaks and the projections tending towards decreases in dry season rainfall, offset partially by increases in wet season rainfall (Government of Mozambique, 2019).

Research in the region has shown that significant impacts on the water balance in river catchments can be observed if the changes in the mean annual precipitation jointly impact on streamflow fractions of surface runoff, lateral flow and base flow (Mango et al., 2011). Land cover change detection for 2001, 2009 and 2021 shows gradual reduction in low density woodland (6.53%) followed by mountain forest (6.21%) and wetland (0.08%); and this is matched by increase in wooded grasslands (5.99%). This seems to be a non-anthropogenic driven succession cutting down of trees for seasonal and other land uses. The corresponding increase in high and medium density woodlands are direct land use driven succession vegetation transitions. A 0.9 % percent woodland forest loss in the whole of NSR was reported between 2001 and 2014 and largely attributed to expanding agriculture around settlements and along main roads (Allan et al., 2017). The threat of vegetation cover loss effects by rising temperature because this is likely to increase in the potential evapotranspiration and this affects the balance between precipitation and evaporative demands.

5.2 Conclusions

5.2.1 Changes in LULC and management needs in Incalaue catchment.

The study showed that river sub-catchments as LUL hydrologic divisions are useful to map environmental differences, change and LULC over time and space. This study used landscape characteristics for mapping LULC; and added detailed vegetation changes identification to effectively characterise changes in a hydrologic context over studied time. This study provides information useful for guidance to conservation institutions in Mozambique for vegetation cover trend analysis and conservation management hotspot areas in seasons.

This study showed that vegetation cover dominates among LULC types and holds potential for use in environmental water availability monitoring. Changes LULC were assessed for hydrology inferences using relief and vegetation spatial and temporal patterns to detect changes for years 2001, 2009 and 2021. This study provides information useful for guidance to conservation institutions in Mozambique on vegetation cover trend analysis and potential conservation management hotspot for water resources in a wildlife reserve like NSR.

There are human settlement areas and these have expanded over time; and the study shows a need for mitigating human-wildlife conflict in the green vegetation riverine areas during the dry season. There is a challenge for LULC management due to the Mozambican legislation which creates a danger of human settlement, ownership and use of land; and potential degradation in this wildlife conservation area. The study showed that vegetation cover and its spatial and temporal cover change hold potential for landscape-based conservation planning and environmental monitoring in Incalaue river basin

The study showed that human settlement areas have expanded over time; and the study showed a need for mitigating human-land use to mitigate degradation of sensitive water source and groundwater recharge areas. This was revealed by results showing groundwater recharge and in an area with human settlements there and in vicinity. The existence of road and footpaths further showed potential for expansion of human settlements in those areas. There was need to secure these areas because of the challenge in land ownership rights in the area. The Mozambican legislation which creates a danger of human settlement, ownership and use of land; and potential degradation in this wildlife conservation area.

5.2.2 Influences of soils and LULC on rainfall-runoff and water source areas

There was a good model performance in modelling rainfall runoff (RMSE = 0.193) using soil data available at IIAM (government of Mozambique, classified LULC data by this study and NASA-POWER satellite climate data. This shows potential for using SWAT model and remote data for modelling the river catchment and similar catchments and to upscale to a wider catchment for hydrologic modelling.

Soils were dominated by sandy loams which class does not have strong capillary attraction and dominance of particle sizes largely in the classes of >2.5 mm class all of which explain high sedimentation rates observed. Such are areas that don't support much of deep and medium rooted vegetation and are not good at supporting water infiltration thus allowing more rainfall runoff. Soils analysis showed that only showed that it is only sand content and bulk density that can related for all the sampling sites. The study results above interestingly show that FAO characterization of the soil misses the top-soil layers and characteristics and these are even most important on river flow generation, composition and quality. Dambo springs are the main annual water sources for both human beings and wildlife in the basin in the dry season. Results do not indicate any differences in source areas of springs beyond a uniform geology of the area. Contributions of climate and LULCC to water availability.

5.2.3 Climate and LULC effects on river flow

The SWAT performance was considered acceptable basing on successful validation using fieldwork collected river flow data; and successfully modelling rainfall and river flows trends reported by community. Over the studied time period (2001 - 2021), by relative proportions, the model showed that LULCC had contributed a little more than climate to changes in river. Combined, land use/cover and climate were both found to have just above 0.5 contribution to rainfall runoff fractional contribution to translation into river flow.

CHAPTER SIX

CONTRIBUTIONS OF THE STUDY AND RECOMMENDATIONS

6.1 Scientific contributions of the study

The following are the scientific contributions of the study:

i. This was the first quantitative hydrology study in miombo ecosystems in NSR. It provided scientific contributions on understanding rainfall and river flow relationship and assessed groundwater recharge evidence to recommend environmental management needs.

ii. The study used dominant HRU characterisation with focus on land use and variations in soil while making reference climate and slope reflection in river flow variations to map landscape patches of conservation value for potential seasonal habitats conservation

iii. This was the first study to assess dry season water sources and characterise them as HRUs in the miombo ecosystems in Mozambique.

iv. Dambos had not been studied for relevance in terms of water availability for people and wildlife as well as they water source sharing and this was covered in this study.

v. Historical rainfall and river flow data were not available to be used in modelling so the study innovated assessment by using community validation of rainfall runoff that was modelled using NASA-POWER satellite data as well as field collected rainfall, river flow and LULC data using SWAT model.

vi. The modelling part tests a new remote dataset in the area; and then the approach contributes to hydrologic modelling research studies on reduction of uncertainty by detailed catchment hydrologic data collected before upscaling for use in modelling river basins with remote datasets. The study contributes to an already identified gap physically-based models by contributing ideas about their capabilities for hydrologic prediction with both gauged and predicted data to obtain realistic estimates of the uncertainty before upscaling.

vii. This study contributed information on relative contribution of land use/cover and climate to river flow. This is important information for management to plan and enforce land use as well as important base for scientists to further model this relationship under any possible scenarios.

6.2 Contributions towards management of NSR and other conservation areas

The following are contributions towards environmental management and policy reviews.

i. This study contributed knowledge that can be useful for land cover conservation to secure sustainable water availability for people and wildlife in the reserve.
ii. The need for government consideration of an alternative water supply system for people to avoid water shortage effects of any dambo springs yield reduction.
iii. The need to plan for the land use by human communities in the reserve to avoid wet vegetation zones in the dry season as they are possible safety and refugee zones for non-migratory wildlife.
iv. The need for consideration of scientific implication of the Mozambique land policy with reference to wildlife conservation areas.

6.3 Recommendations

Based on the above findings, the following recommendations were made:

(a) Research and monitoring needs

The study recognises there is existing research in the study area but this has largely focused on LULC. In context of the study area being wildlife reserve, this study showed the there is need for consistent and conservation targeted environmental research to inform policy and land use; and land cover planning. Spatial and temporal trend analysis of land use and land use/cover done in this study can be useful in landscape environmental conservation for development of hypotheses on hydrological processes underlying vegetation diversity patterns.

(b) Infrastructure Development

There is a need for the following infrastructure development to support the research dimension in the study area. A research and monitoring station is require for the river catchment or connecting it to existing ones. These research stations need to be equipped with important basic quantity and water quality monitoring field and laboratory equipment to help research scientists collect and analyse data. There is need for automated weather stations and river flow gauging stations that can transmit data remotely. This should be supported by routine checks.

(c) Establishment of dambo springs catchments protection

The study showed the value of the protected springs and community dependence. There are human activities in areas around dambos including agriculture and some settlements in the dambo micro-catchments. It is recommended that conservation efforts should be put in place to prevent any activities. The field data collected and observations were similar to community reports on dry season situation with regard to water availability means vulnerability for human population and this calls for water supply or safe water access and sustainable solutions attention. The presence of a borehole which could not pump properly because the handle was broken showed potential of groundwater supply in the area but this needs to be further explored.

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APPENDICES

The papers that were published and combined into this thesis are presented below.